# Journal of Applied Physics

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## *"Let us go forward . . . "*

AN important phase of the activities of the American Institute of Physics is the stimulation of industrial research based on physical principles. This development is in line with the efforts of the American Physical Society to enhance the standing of physics as a profession. To help establish a new medium devoted to the interests of the applied physicist, the Society is turning over the good will and ownership of the journal *Physics* to the American Institute of Physics. The financial responsibility for the new journal will be in the hands of the Institute while the editorial staff will be appointed by the Institute from recommendations by the American Physical Society.

The *Journal of Applied Physics* will carry on the program initiated by its predecessor in the publication of research papers. In addition new features will be developed which will in many ways alter entirely the character of the journal. Papers describing in a broad way the application of physics in particular industries or in the borderline sciences will be published. Periodically some particular laboratory will be discussed with emphasis on the personnel and organization rather than on the buildings and equipment. Biographical sketches of those who are applying physics will be included. To aid those in the applied physics field, reviews of recent important articles in other journals will be published along with short sketches concerning the authors of these papers. Because of the interests of the readers of a journal of this kind in advertising, the advertising pages now carried in *The Review of Scientific Instruments* will be carried in this journal also.

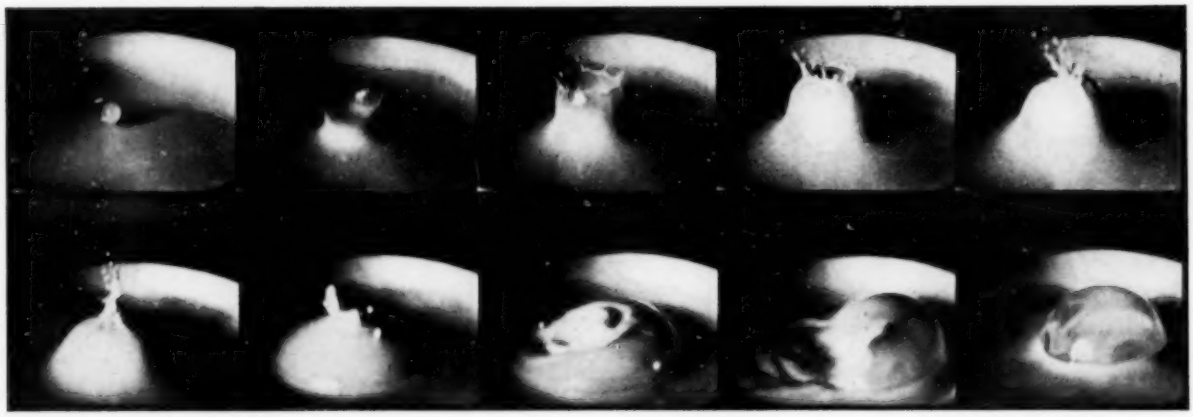
***"Let us go forward, then, with confidence in the dignity of our pursuit. Let us hold our heads high with a pure conscience while we seek the truth, and may the American Physical Society do its share now and in generations yet to come in trying to unravel the great problem of the constitution and laws of the Universe."***

**—HENRY A. ROWLAND,**
***first presidential address***

So far, only the content of the *Journal of Applied Physics* has been discussed. The officers of the American Physical Society and of the Institute are convinced that a journal of this kind to be successful must be made as attractive as possible. With this in mind, the new journal will contain many striking photographs illustrating applications of physics.

This new journal is your journal. Its character is just being formed. To go forward in stimulating research and in raising to an ever increasing height physics as a profession we need your support. The board of editors will appreciate any comments or suggestions which you care to make.

THE EDITOR



A selection of frames printed from a high speed motion picture showing the formation of a large air bubble by a drop splashing into a liquid surface from a height of 8 ft.

# High Speed Photographic Methods of Measurement

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MEASUREMENTS are the basis of scientific and engineering investigation, and may require any one of a multitude of different methods of varying complexity. The particular form of measurement used is determined by the nature of the problem and the degree of precision desired; however, there are very few exceptions to the rule that "the easiest and quickest method is best." In that province of physics that concerns rapid mechanical motions, the high speed camera (because of its directness and clarity) is one of the "quickest and easiest" methods of motion analysis.

High speed photography permits the observer to obtain a picture or a series of pictures accurately recorded as a function of time, permitting detailed study of the action. The pictures of a series may be analyzed frame-by-frame, or they may be projected on the screen in ultra-slow motion, permitting the eye to see vagrant actions that are normally imperceptible.

Although high speed photographic methods have been in use for many years, particularly by workers in the ballistic field using silhouettes, the general use of such methods has been seriously limited because of the complexity of the apparatus and the ensuing difficulties of manipulation. Electronic devices that have been developed in recent years have made possible vast improvements in apparatus for making high speed photographic studies. Several types of apparatus that have been in active useful operation at the Massachusetts Institute of Technology for the last few years are described and illustrated in this paper. The cooperation of the General Radio Company has been very helpful in this development, and a number of stroboscopes and cameras have become available to the public through them.

Further interest in high speed motion-picture work has resulted due to the recent availability of different types of high speed nonstroboscopic cameras. Several of these are listed in this paper, together with a very brief description of their operation and applications, since they are particularly applicable to some types of problems.

### *Methods of Taking High Speed Photographs with Light from Electrical Discharges*

The basic phenomenon in the methods of taking high speed photographs described in the following is the violent discharge of an electrical condenser through a gas-filled tube or gap. An intense flash of light of very short duration is emitted by the gas at the instant of discharge, and this light is used in one of a variety of ways to expose the sensitized film in a camera. Of the many factors that influence the variation of the intensity of the light as a function of time, the following are the most important:

1. The magnitude of the voltage to which the condenser is charged.
2. The capacitance of the condenser.
3. The inductance of the discharge circuit including the internal inductance in the condenser.
4. The dimensions of the gas-filled tube.
5. The kind of gas used in the tube or gap.
6. The pressure of the gas.
7. The material of the electrodes.

The performance characteristics of several of the arrangements used at M.I.T. for taking high speed photographs are given below with a description of the apparatus. Papers describing other flash methods are listed in the bibliography.[1–7]

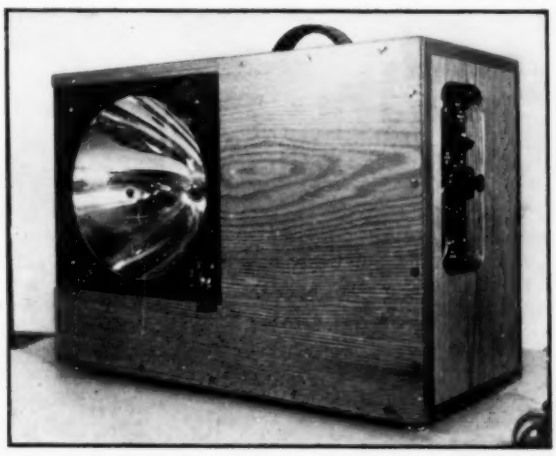

FIG. 1. A photograph of a spark light source constructed as a portable unit.

### *Single-Flash Apparatus*

A device producing a single flash of light has been found very useful. The particular one described is portable and requires less than 100 watts of power from a 110-volt, 60-cycle outlet. The flashes of light last about $10^{-5}$ seconds and are bright enough to expose adequately common grades of film in that short interval of time, with ordinary camera equipment. Fig. 1 shows a photograph of a complete portable light source of this type, and Fig. 2 is a wiring diagram of the arrangement. The flash of light is produced in a gap in air by the violent discharge of a 3-microfarad condenser that has been charged to about 15,000 volts. Approximately 10 seconds are required to charge the condenser before the flash. Control of the instant of flash is obtained by applying a high potential to a third electrode placed near the gap. The main gap electrodes and the condenser potential must be adjusted until flashover is imminent when the condenser is fully charged. The application of a high voltage impulse to the third electrode causes the main gap to break down at the desired instant.

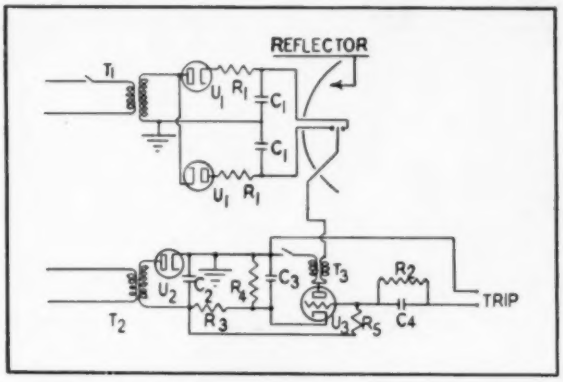


FIG. 2. A wiring diagram of the spark light source (Fig. 1).

| | | | |
|---|---|---|---|
| $T_1$ | 110–5500 volt transformer | $R_2$ | 1 megohm |
| $T_2$ | 110–600 volt transformer | $R_3$ | 10,000 ohms |
| $T_3$ | spark coil 30 : 1 ratio | $R_4$ $R_5$ | 100,000 ohms |
| $U_1$ | type 878 kenotron | $C_1$ | 6 mf |
| $U_2$ | type 80 or 81 rectifier | $C_2$ | 1 mf |
| $U_3$ | type FG-17 thyratron | $C_3$ | 0.5 mf |
| $R_1$ | 50,000 ohms | $C_4$ | 0.0001 mf |

The control of the starting time may be accomplished in a variety of ways. Frequently the most convenient method has been to use an electrical contact to trip a thyratron pulse circuit, though several other methods have been devised. One such scheme, which has been used

successfully, is to employ an amplified signal from a photo-cell caused by the interruption of a beam of light. In either case the function is to trip the thyratron ($U_3$ of Fig. 2) which in turn acts as a switch to discharge the energy in the 0.25-microfarad condenser $C_3$ into the primary of a step-up transformer (spark coil). The high

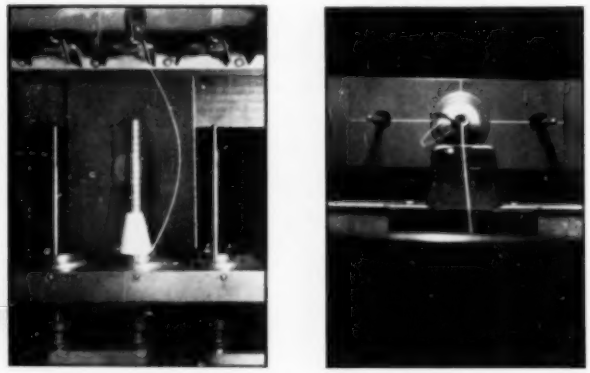

FIG. 3. Horizontal and vertical view of a textile spindle. (Exposure about $10^{-5}$ seconds.)

voltage from the secondary terminal is connected to the third electrode mentioned above, and the spark from it to either or both of the main electrodes results in a breakdown of the main gap with the accompanying flash of light.

Several examples of accurately-timed single-exposure photographs taken with this type of apparatus are included in the illustrations. The cover photograph, one of many taken by Professor Zavarine, shows steel being quenched. Fig. 3 shows two such photographs of a textile spindle operating at full speed of about 10,000 r.p.m. One of the pictures is taken from above and shows the spiral form of the balloon (as the loop of yarn is called). Fig. 4 enables the direct measurement of the distortion of a full-size airplane propeller in operation. As noted in the caption, the actual deflections of the propeller can be measured on the photograph with a precision of about 0.02 inch, although the propeller is rotating at full speed.

An electrical arrangement capable of taking exposures much shorter than those obtainable with the apparatus of Fig. 1 has been developed. With this apparatus it has been possible to take photographs by reflected light at $f$:8 in less than two microseconds. The gap consists of a two-inch length of Pyrex tubing, 6 cm inside diameter, filled with argon at atmospheric pressure. The addition of air to a pressure of several mm of Hg has been found to reduce appreciably the afterglow in the gas and at the same time to raise the breakdown voltage so that the full high voltage can be used directly on the tube. Inductance in the condenser $C_1$ and in the leads to the argon lamp must be reduced to a minimum for obtaining the shortest exposures.

Control for starting the flash at the desired instant is effected in the same manner as in the spark apparatus, namely, by the use of a third electrode excited suddenly with a high potential at the instant desired for starting. In this case the third electrode is an external band around the tube. A complete wiring diagram especially arranged for photographing bullets in flight is shown as Fig. 5. The igniting spark is started by an impulse initiated by the impact of the sound wave accompanying the bullet upon a piezo-electrical crystal microphone. Consistent and accurate timing of the flash of light with respect to the position of the bullet has been obtained with this arrangement. It is interesting to note that preliminary adjustments can be made

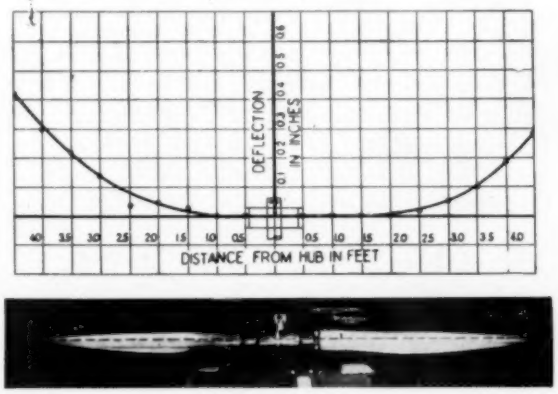


FIG. 4. Side view of a 9′ 6″ aircraft propeller rotating at 1900 r.p.m. is shown in lower part of the figure. The curve above is a plot of the deflections along the propeller blades as measured from the photograph. The deflections are known to about 5 or 10 percent, which means about 0.02 of an inch on the propeller. The exposure time was about $10^{-5}$ second and the instant of exposure was controlled by a contactor on the shaft of the motor. The picture was taken on a glass plate (5″×7″) and the deflections were measured from the negatives with a microscope comparator. The photograph and measurements were made by Professor C. S. Draper, with the cooperation of the authors.

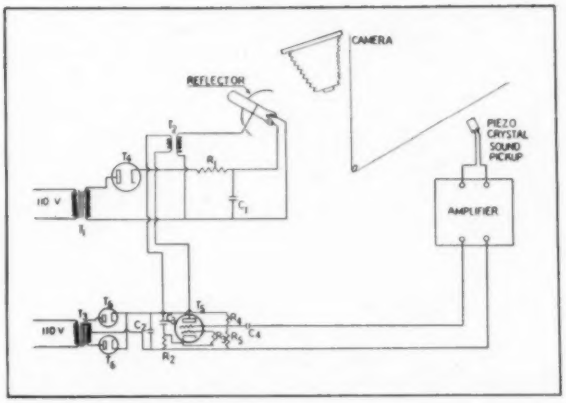


FIG. 5. A wiring diagram of a flash-producing apparatus.

| | | | |
|---|---|---|---|
| $T_1$ | 110–8000 volt transformer | $R_2$ $R_3$ | 10,000 ohms |
| $T_2$ | spark coil 30 : 1 ratio | $R_4$ | 100,000 ohms |
| $T_3$ | 110–600 volt C.T. transformer | $R_5$ | 50,000 ohms |
| $T_4$ | type 878 kenotron | $C_1$ | 0.2 mf condenser (small internal inductance) |
| $T_5$ | type 631-P1 strobotron | $C_2$ | 10 mf |
| $T_6$ | type 80 rectifier | $C_3$ | 4 mf |
| $R_1$ | 1 megohm | $C_4$ | 0.1 mf |

visually, since the position of the bullet at the instant of the flash can be observed with the eye. After the necessary adjustments have been made visually to locate the bullet at the desired part of its trajectory, the exposures are made.

Fig. 6 is a photograph of a 0.30 caliber bullet taken by means of the apparatus described above. Attention is called to the fact that the rifling marks can be seen, although the velocity was 2600 ft. a second. At this velocity a microsecond exposure will produce a blur of 0.03 inch on the bullet.

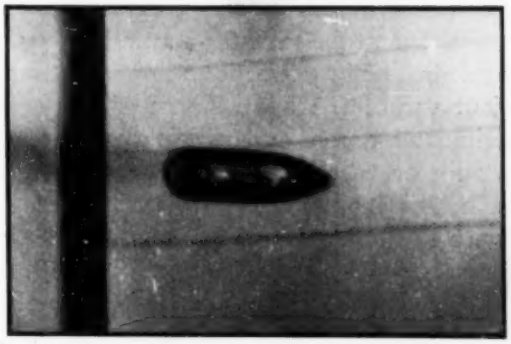

FIG. 6. A photograph of a 0.30 caliber bullet traveling 2600 ft. per second. Exposure about 1 or 2 microseconds. Taken at *f*:7.7 on Verichrome film. (This photograph was taken at the Watertown Arsenal and is reproduced through the courtesy of the War Department.)

### *High Speed Motion-Picture Apparatus (Stroboscopic-Light Type)*

A series of photographs with very short exposures made at high rates of speed have proved to be very useful in studying mechanical problems, since transient motions thus become measurable. The details of displacement and distortion of objects in rapid motion are directly observable as a function of time on the film, and velocities and accelerations may be easily calculated. Furthermore, the film can be projected as a motion picture showing the action at a greatly reduced speed so that the eye can see in detail what is going on. The camera capable of taking 1200 pictures a second on standard 35-mm film is shown as Fig. 7. Exact timing of the flash of the stroboscopic light with respect to the motion of the film is essential to subsequent steady projection of the resulting high speed pictures on the screen.

In the latest camera, synchronizing of the flashing of the light source with the film is

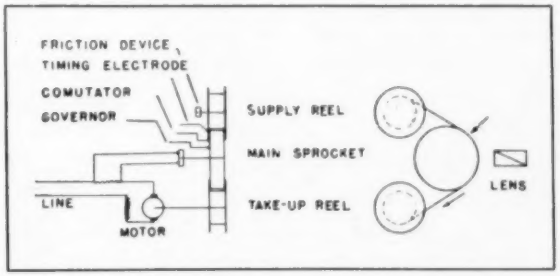


FIG. 7. A schematic diagram of a continuously-moving film camera, capable of 1200 frames a second at 35 mm or 6000 frames a second at 8 mm.

accomplished by the use of a molded Bakelite contactor mounted directly on and at the back of the main sprocket. To take pictures at a uniform rate it is necessary to maintain a constant speed of this sprocket, and at the same time vary the speed of the take-up reel. This problem has been solved by the use of a governor motor of the series type driving the camera through the take-up reel but putting the motor governor on the sprocket shaft. Fig. 7 is a diagram of the essential parts of the camera.

Most problems require an accurate permanent record of the film speed, and the most convenient record is one put on the film at the time the

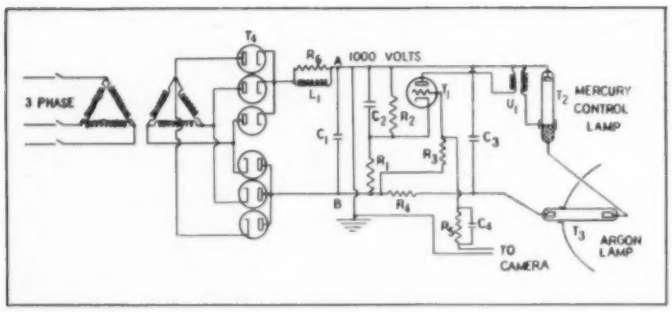


FIG. 8. The wiring diagram of a source of stroboscopic light for taking high speed motion pictures.

| | | | |
|---|---|---|---|
| $T_1$ | type FG-67 thyratron | $R_3$ | 5000 ohms |
| $T_2$ | mercury-arc control tube | $R_4$ | 400 ohms |
| $T_3$ | high pressure argon-filled stroboscope lamp | $R_5$ | 1 megohm |
| | | $R_6$ | 200 ohms |
| $T_4$ | type FG-32 rectifier tubes | $C_1$ | 30 mf |
| $U_1$ | spark coil | $C_2$ | 1/8 mf |
| $L_1$ | 1 henry choke | $C_3$ | 1 mf 1200 flashes/sec. |
| $R_1$ | 1000 ohms | | 2 mf 600 flashes/sec. |
| $R_2$ | 100,000 ohms | | 4 mf 300 flashes/sec. |

Additional lighting units may be connected across the power-supply terminals $A$–$B$.

exposure is made. To accomplish this, a low-power oscillator which produces a peaked wave of about 10,000 volts maximum at 60 cycles is used to produce a spark to the edge of the sprocket. This makes a series of dots spaced one sixtieth of a second apart on the edge of the film.

There are several features in this camera which, while not essential, make for ease of operation. Focusing is accomplished by viewing the image through the film from the back. The necessary holes are cut in the sprocket, and a magnifier aids in observing fine detail. Film protectors are used for daylight loading of the camera. Friction catches have been used throughout, so that it is unnecessary to undo bolts or nuts in the course of normal operation. The front of the camera is so constructed that almost any standard lens may be quickly mounted. The reels hold approximately 125 ft. of film and have a large core so that their speeds are kept down to a reasonable figure. At 1200 frames a second the large sprocket turns 3600 r.p.m., and the reels vary from 4500 to 7500 r.p.m. It is necessary to have a friction device on the supply reel to prevent overrun.

A wiring diagram of the electrical apparatus for producing the stroboscopic light that makes possible the high speed motion pictures with the continuously-moving film camera is shown in Fig. 8. The light is produced in argon lamps $T_3$ that are connected in series with mercury-control lamps $T_2$. The flash of light is produced in the argon tube at the instant the condenser $C_3$ is discharged through it and the mercury tube in series. The function of the mercury tube is to provide a rapidly-deionizing series element which prevents uncontrolled restarting of the argon tube. This enables the argon lamp to be flashed successfully at high frequency. The deionization time of the argon tube is comparatively long, since the gas pressure is relatively high.

High pressure argon lamps have proved to be more satisfactory for producing stroboscopic light than mercury lamps, principally because of the lack of the temperature effects which are so serious with the latter. Furthermore, the volume of the arc can be made quite small in the high

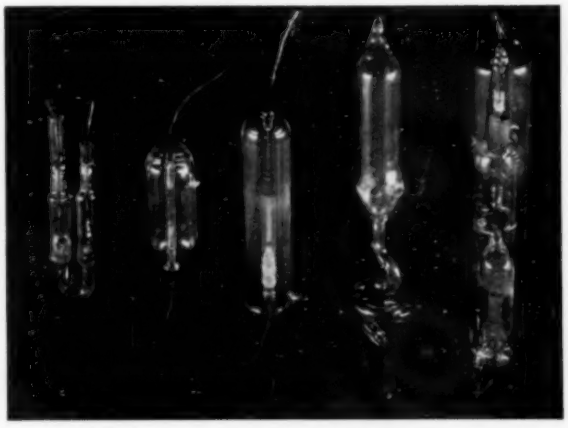

FIG. 9. Experimental argon-filled stroboscope lamps.

pressure argon tube with the accompanying high intrinsic brilliancy which is so important for the efficient use of the light. Fig. 9 shows several experimental argon lamps. Most of them use quartz in contact with the active discharge in order better to withstand the high temperatures that are encountered. The pressure of the argon gas used in different lamps ranges from 10 to 76 cm of Hg. Aside from the introduction of the series high-pressure lamp, the operation of the electrical circuit is identical with that which has been previously described.[8, 9]

A few examples of high speed motion-picture photography are included as illustrations. The

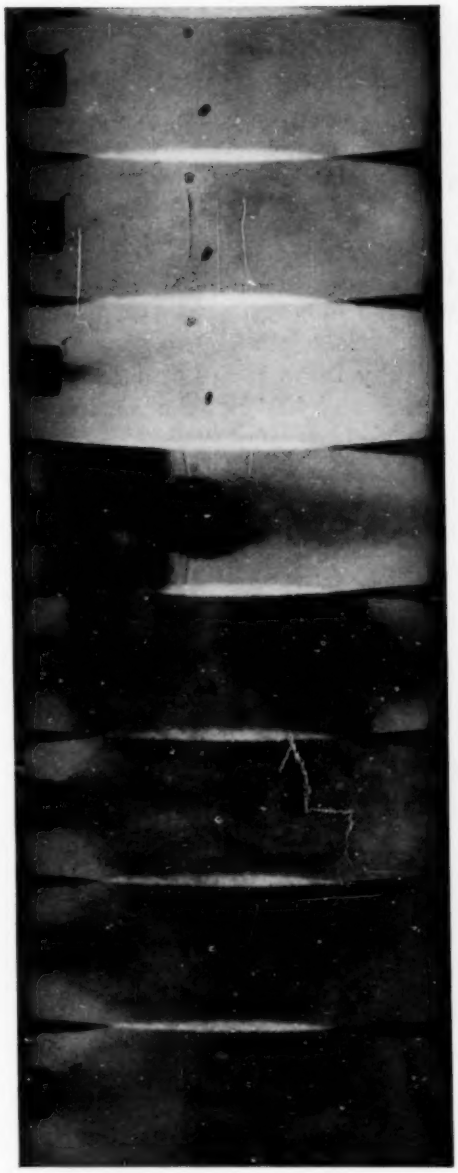

FIG. 10 (left). High speed motion picture taken at 3000 per second, to show gas leakage around the charge in a shotgun. A condition satisfactory in this respect is shown in the above photograph. The charge is shown in the fourth picture from the top as it has just emerged from the barrel. A slight amount of gas is shown coming from the barrel in the picture just above it. Sound waves are visible in the second picture from the top, but they are faint and may not be visible in the reproduction. (Courtesy of the Winchester Repeating Arms Co., New Haven, Conn.)

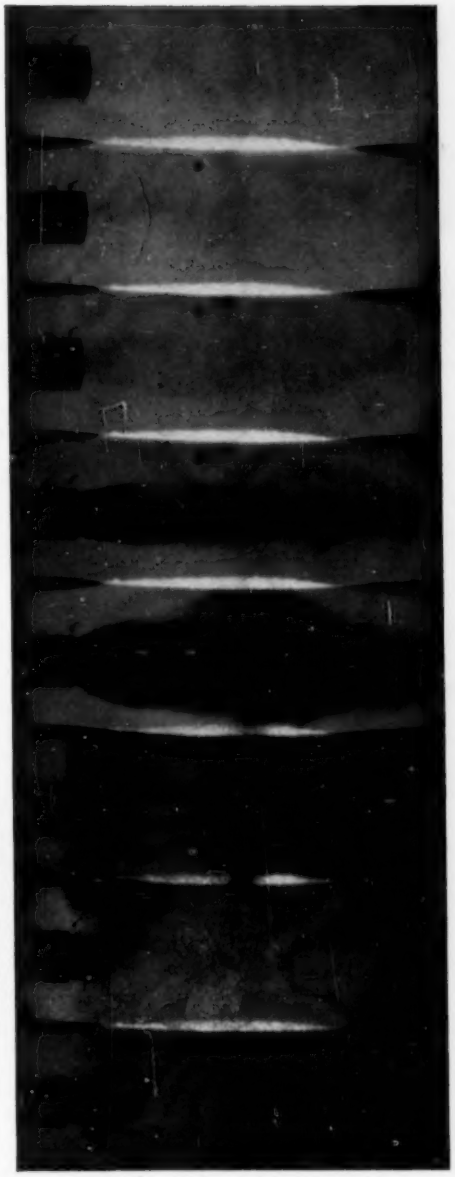

FIG. 11 (right). This series of pictures of the muzzle of a shotgun, also taken at 3000 a second, shows considerable leakage of the gas before the charge emerges from the barrel in the sixth picture from the top. A sound wave is evident in the second picture from the top. (Courtesy of Winchester Repeating Arms Co., New Haven, Conn.)

photograph on page 2 shows the formation of a large bubble on a liquid surface by a drop splashing from a great height. The emergence of charge and gases from the muzzle of a shotgun is shown in Figs. 10 and 11. Fig. 12 shows spray issuing from a nozzle.

The principal limitation of the stroboscopic-light type of high speed motion-picture camera is its inability to record self-luminous subjects, such as electrical arcs and explosions. A different type of high speed motion-picture camera is useful for photographing such subjects. The exposure time in these is very much longer than with stroboscopic light. This is sometimes a disadvantage, and at other times an advantage, depending upon the problem at hand.

### *The Moving-Optical-System Type of High Speed Motion-Picture Camera*

By the use of a moving-optical system whereby the image cast by the lens is held stationary with respect to a continuously-moving film, it is possible to take photographs at high rates of speed, due to the elimination of the intermittent mecha-

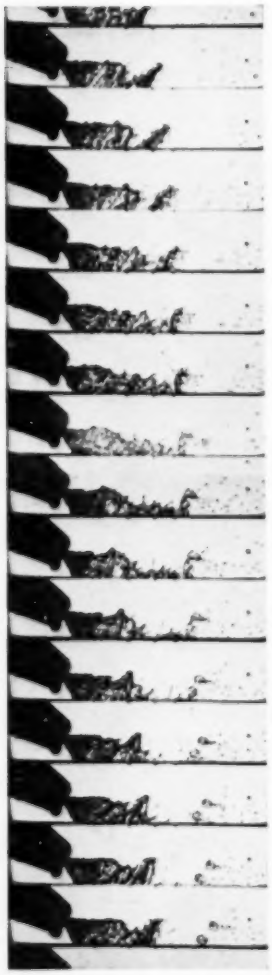

FIG. 12. Motion pictures taken at 6000 a second showing liquid emerging from a pressure spray nozzle. The spinning action of the opening in the nozzle spreads the material into a thin film. As the film collapses, it entraps air, forming spherical hollow particles, two of which can be seen at the bottom of the series of pictures. The low density of some spray-dried products is due to the entrapped air. (Courtesy of Lever Brothers Company, Cambridge, Mass.)

nism of the common motion-picture camera. Three types of moving-optical systems have been developed, employing, respectively, rotating lenses, rotating mirrors, and rotating prisms. Several cameras with moving-optical systems are in use. Their principles of operation are briefly noted below, and papers describing them more completely are listed in the bibliography for the convenience of those who may care to investigate them further. Such cameras require ordinary lighting equipment with intensity proportional to the speed.

A 16 mm high speed motion-picture camera capable of operating at speeds of several thousand frames a second has been developed by Fordyce Tuttle of the Eastman Company. This camera, Fig. 13, has a rotating prism between the lens and film which holds the image stationary with respect to the film during the exposure time. An accurate clock developed by the Western Electric Company is incorporated with the camera and is photographed on the edge of the film. The Electrical Research Products, Incorporated, 250 West Fifty-Seventh Street, New York City, are the distributors of this camera.

The Zeiss-Ikon Company has made available another type of high speed motion-picture camera. This particular model relies upon a system of moving mirrors to prevent blur on the continuously-moving film. Distributors are the George Scherr Company, 128 Lafayette Street, New York City.

A camera using matched rotating lenses and shutter has been used by the Allgemeine Elektrische Gesellschaft, Berlin.[10–11] The Merlin and Gevin Company, Grenoble, France, manufactures a camera of the moving-lens type, which is described in their catalog.

The bibliography lists articles describing the moving-lens camera of Jenkins, the remarkable mirror camera of Suhara, and others.

The exposure time with the above cameras is usually about half the average time per frame,

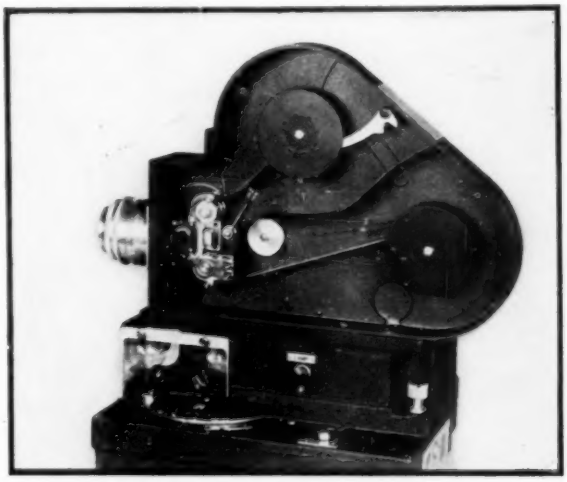

FIG. 13. Eastman rotating-plane-prism high speed camera with magazine cover removed. The timing clock (Western Electric Company) is below the camera.

although this time can be decreased, if there is sufficient light. In some cases the motion of the objects photographed during the exposure interval results in a blurred image on the film, this being the case when close-up shots of rapidly-moving objects are photographed. In the Jenkins camera the exposures overlapped so that the exposure time was longer than the interval of time between pictures.

### *Conclusions*

The art of high speed motion-picture photography employing compact, portable apparatus is relatively new and still undergoing active

development. Despite its youth its industrial applications have already been many and varied. There is every reason to believe that its usefulness may greatly expand as knowledge of its simplicity and easy application diffuses to those confronted with problems which it can solve.

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*I often say that, when you can measure what you are speaking about and express it in numbers, you know something about it, but, when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind. It may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of Science, whatever the matter may be.*

—LORD KELVIN

# Building

## The forgotten child of physics

By JOHN ELY BURCHARD
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THE modern building has two parts—a shell and equipment to make that shell habitable. The shell is relatively old, the equipment relatively new. Both are children of physics—to the younger the father has been lavish; to the elder of late years he has accorded scant recognition.

While Aristotle's celestial "aether" and his four terrestrial "simple bodies" were still the belles of the scientific ball, Archimedes had stated laws of equilibrium which for practical purposes serve today. Galileo established the essentials concerning transverse strength and strain in beams. The mathematical physicists of the middle 19th century, Euler, Lagrange, Poisson, Saint Venant, Kirchhoff, set forth the principles of elasticity upon which modern structural design rests. Then the cosmos beckoned.

Today's buildings are made of materials which should not attribute validity to the old constants and the old hypotheses of design. Yet physics, the father, still lets his child worry along under the ministrations of a guardian, the engineer, who knowing well his own limitations and striving hard enough within them to bring the child to a suitable adulthood has simply been insufficiently equipped for the task.

It may be only fair, however, to point out some of the ways in which modern applied physics *is* working to improve buildings. It would be laboring the obvious to discourse on the myriad ways in which applied physics helps us every day in our homes. Here it may better serve to indicate some transitions now in progress. To bring the field within reasonable scope, let us choose for examination one quite antiquated type of building, the school.

Good work in a school depends upon minimizing fatigue. Fatigue is almost wholly a matter of environment. The physicist in collaboration with the physiologist and psychologist has been working steadily to reduce the fatigue factor through the media of temperature, air, light and sound controls.

Until recently methods of heating buildings have been, to say the least, casual. Long ago we learned that some room air temperatures were fairly comfortable while others were not. But it was not so long ago when we began to appreciate that what heating a building should seek to achieve is no more or less than a healthy, stimulating and comfortable environment. Scientific approach to the problem of bodily comfort has revealed that the human body should give off roughly 400 b.t.u.'s per hour, depending somewhat upon the individual and his degree of activity. This heat may be dissipated in three different ways simultaneously:

(1) By diffusion to the surrounding air, the amount being a function of air temperature and motion but equaling on the average about 19 percent of the loss;

(2) By evaporation of moisture passing through the skin or exhaled from the lungs, a function of the relative humidity and movement of the air but averaging 25 percent;

(3) By radiation from the body to surrounding visible solid surfaces whenever they are colder than the body itself, averaging about 56 percent.

Working only on the first of these methods of dissipation, we have in the past heated and dried our air excessively. Our lungs function better and we feel more energetic at lower than conventional temperatures and higher than conventional humidities. On the other hand, heat drawn from the body to cold walls and window panes induces a sense of chill.

Now, radiant-heat loss is by far the largest single loss suffered by the body. It is possible to obtain the same degree of comfort at 70°F in a properly insulated wood-frame house as at 73° in the same house uninsulated, solely because the radiant-heat loss to the walls has been reduced appreciably by this insulation (56 percent to 46 percent) permitting an increase in the loss by diffusion (25 percent to 32.5 percent) with correspondingly increased comfort.

The idea at once suggests itself that further improvement might be expected by applying heat directly to the building structure. A limit, however, may be reached with the air at around 60° since it apparently cannot be kept indefinitely at a temperature much below that of the enclosing surfaces without requiring too frequent air changes and too high air velocities.

There has been some experiment with heating the walls—that is, with radiant heating—in this country, and considerably more in Great Britain. Indeed, the only building of consequence in the United States which I know to be heated by radiant panels is the British Embassy in Washington. Experiments in schools in England have indicated that with radiant-heating panels not only were heating costs reduced but comfort, health and efficiency increased. These results are tentative because British standards of comfort are different from ours and measurements of the psychological factors, comfort and efficiency, are not yet exact. None the less, it appears amply clear that through study of the fundamentals of heat, physics will revolutionize our methods of building heating.

While radiant heating is not yet a matter of general public interest, its cousin, air conditioning, is a headliner—and like most headliners frequently misquoted. One of our greatest losses in education comes from more or less constant reinfection with low grade infections. Dr. Wells at the Harvard School of Public Health has recently indicated that by the use of ultraviolet light it seems possible to kill the germs of influenza. Many hospitals even now irradiate their operating rooms on the chance that the rays may have lethal effect at least on some germs. Very soon, through work by physicist and bacteriologist, the air in a room may be rendered relatively germ-free by x-ray. It is by no means impossible that the physicist will also devise methods (perhaps those of electrostatic discharge) to remove pollen and other unhealthy air-borne dusts. Indeed, Professor Drinker's experiments in air mixtures suggest even the possibility of scientific artificial air blending. Modern air conditioning cannot avoid the responsibility for making air of public buildings much less infectious than it is today.

Even after sources of infection have been removed, schools have a serious problem in connection with odor. At present we circulate some 30 cubic feet of air per student per minute through our classrooms though all we need to eliminate carbon dioxide and supply adequate oxygen is perhaps 4 cubic feet. The balance is to eliminate odors which, though not known to be harmful, do create an atmosphere of stuffiness and very likely reduce efficiency. Problems of odor may at first glance appear to be more in the province of the chemist than of the physicist, but this much may be said: One necessity in any scientific study of any problem is the existence of units of measurement. The measurement of odor is in its infancy. I can go home tonight, and if my wife can transfer decibels and footcandles into aural and visual conceptions I can give her a very close idea of how loud we were here and how much light we had here. But I cannot with the descriptive means at my disposal give her the

*This paper, presented at the meeting of the Founder Societies of the American Institute of Physics in New York, October 30th, has created considerable comment. Quotations in the newspapers of a single paragraph have given an impression which a reading of the complete paper does not convey. The Editors feel that Mr. Burchard has performed a real service in bringing to light the need for applied physics in the building industry. This statement does not imply that they necessarily agree with all of the opinions expressed.*

remotest conception of how we smelled here. We now see a serious effort on foot to establish a nomenclature of odor that will mean something. This may lay the groundwork for studies in odor intensity. The search for the sniff-meter may be arduous, for the olfactory nerves are highly sensitive. But so long as the human sniff is a poor counterpart to a photronic cell science will seek to obtain better means of describing odors quantitatively and qualitatively. However chemical may be the problem, we may be quite certain that when an instrument is in question the physicist will not be far behind.

The bad effect of noise in the schoolroom has belatedly been recognized. It is now well established that efficiency drops rapidly as noise increases. But the acoustical problem in schools is aggravated because, at least according to current thinking, schools must be located near the centers of population of the areas they serve. Noise levels much over 40 decibels above the threshold of audibility are definitely undesirable, yet city streets have a prevailing intensity of 70 decibels and may reach 90 decibels above the threshold, while 60 decibels above the threshold is by no means uncommon even in the suburbs. Some improvement is possible in planning, of course, by placing rooms least affected by disturbance, such as gymnasia and vocational rooms, on the noisy side to act as shields for the others; and conventional methods of acoustical treatment may produce a reduction of something under 10 decibels without loss of audibility. But a more basic approach will result in the design of buildings with noise-reduction properties equaling or approximating the difference between the external and the desired internal noise level. Such an approach is entirely possible in the light of current physics. It might, for example, result in a building with fixed windows with sound-isolating properties equal to those of the walls or, even more conveniently, a windowless building.

We spend much time and money examining the eyes of school children, and we know that poor or insufficient light is a source of fatigue and inefficiency. Yet modern schoolrooms are still designed pretty much on the catch-as-catch-can principle so far as illumination is concerned. Fifty years ago it would have been impracticable both technically and economically to supply even 10 footcandles of light throughout a classroom. The standard now in process of revision will probably call for from 10 to 20 everywhere.

So long as we retain windows one of our greatest problems will be to reconcile light conditions near the window with those at the interior wall. On bright days the intensity at the window may be as high as 100 footcandles while at the farthest desks it may be as low as 5. The solution at present proposed by physics consists of rows of lights regulated by a photoelectric cell so that as external light intensity diminishes that of the interior is increased to produce essential uniformity throughout the day. There are many collateral problems in connection with lighting which cannot be touched upon. It may be of interest, though, to note a recent contribution of applied physics to architecture in the heliodon or artificial sun used at the late Henry Wright's Town Planning Studio at Columbia, which will permit the design of buildings so that they will have maximum solar light and heat in winter and maximum shade in summer.

This is just one of the ways in which physics is taking the joy out of the architectural profession. The days of the coffee and brandy at a sidewalk cafe, all on the client's time, are over for the architect. No longer can he cover loose thinking about color with words—you have given him a definite and specific dictionary; no longer can he stand before his admiring client and admonish the painter to put in a little more umber. Through the work of physics in color, light, sound and heat, it becomes possible to be definite about things—this will make architecture a less amusing but also a more worth-while profession.

We have seen that windowless buildings simplify the problems of ventilation, of providing radiant heat at all points, of controlling noise and of regulating light. On every count it appears that physics has amply proved the windowless building to be scientifically more efficient. At the same time it has made at least a good case for its ability to substitute artificial sunlight for real. Perhaps none of us here really wishes to see windowless buildings become general, although we all might admit that they would be desirable particularly if we could preserve occasional windows through which to see really beautiful

pictures of the out-of-doors. But much as the windowless building may be regretted from sentimental points of view, regret alone will not defer its advent, particularly as it suggests an interesting and valuable departure in structural design as well—a departure which I shall treat in the second half of my paper.

Perhaps one word of warning ought to be issued to the applied physicist in his search for perfection of interior conditions. As has been demonstrated more than once, and even quite recently in a Cleveland store, perfectly uniform conditions of temperature and humidity are also perfect conditions for sleep. If to this perfection be added uniform and ideal light and sound conditions, there is certainly a possibility that instead of being more efficient we shall all become like the seven Ephesians.

Physics need have no serious difficulty with this problem. It should be possible to impose on the ideal conditions some form of vibration, either harmonic or chattering, that will furnish the necessary stimuli to keep us on our toes. First, however, we must catch our ideal conditions.

Unquestionably physics has rolled up an overwhelming score on the side of making the building more habitable. Before we sit back and bask in too warm a glow, however, let us remember that all this improvement goes on in a relatively unimproved structure. Just as surely as physics is to be praised for its lavish gifts to the building industry in the shape of equipment, so it is to be blamed for neglect of the building itself.

When, in the middle of the last century, physics decided that statics was too simple to be interesting, there may have been some justification for the thought. The equations of elasticity provided for conditions of continuity, for example, but, practically speaking, there was no true continuity of building materials. That earthquakes would destroy buildings was known, but there was no such concentration of essential communal services in one spot as is now made in a central power station; that high winds would create stresses was suspected, but there were no Empire State Buildings defying the heavens to unleash the winds against the temerities of man. While all these things have been changing, physics has made relatively no effort to adapt itself to the new conditions; the engineers have tried, and have done rather well, but need the help of advanced thinking.

The growth of reinforced concrete as a building material has provided us with structures in which the material of column and beam is in many cases essentially homogeneous. The increase of welding in steel structures has resulted in another type of building in which continuity must play its part. Finally, within the last year or so in Great Britain research has made fact out of old suspicion: That even in riveted structures the joints are not the simple pin connections we design for but actually have a degree of rigidity.

Now the equations of elasticity in the hands of a reasonably facile mathematician will yield perfectly sound results as to the stresses and strains in beams and columns if the conditions of rigidity at the joints be known. These conditions, it must be borne in mind, may vary widely. In general, the greater the rigidity of the joint the lighter the beams may be, while the heavier the columns must be. Building designers have often solved the problem by playing safe both ways, assuming considerable rigidity in the design of columns, little in the case of beams. Their buildings have not failed in alarming numbers and thus have met their prime test. But that they have been wasteful of material any designer will admit.

Physics has sought to help us in this problem, which is essentially one of determining the conditions of rigidity. It has, for example, provided us with photoelasticity. But photoelasticity despite continued progress is practically, though not theoretically, limited to two-dimensional systems; the material of its models must be transparent, a quality not usual in most building materials. Hence, analogy must be drawn not only as regards size but also as regards composition and homogeneity which is nearly perfect in the photoelastic model and is usually far from being so in the actual structure.

Subject to the same limitations is the work begun by Professor Beggs at Princeton with a mechanical model method in which conditions of rigidity and moment factors induced thereby may be determined by observation of changes in slope. This method, which requires considerable manual dexterity, has but recently been sub-

FIG. 1. Apparatus used by A. C. Ruge and V. Bush to duplicate on a laboratory model of a water tank the destructive effects of earthquakes.

jected to what seems a simplification by Ruge at the Massachusetts Institute of Technology—an improvement which arose from his related work in stresses due to shock.

But both of these methods and any other model method involving the use of different materials than those in the building, at different scale and under planar conditions, must perforce be applied with a degree of discretion that makes the person applying them a fine artist rather than a scientist, dependent in the last analysis upon his intuitions rather than his positive knowledge. The building industry still needs a method of determining rapidly the stress distributions in existing structures under load and without damaging the structures. That this is possible I cannot assert—to those of us who are regularly bewildered by the marvels of physics, development of such an instrument, perhaps by detecting variations in electric or magnetic properties with minute variations in stress, seems a task to be tossed off some morning by a physicist between his cereal and his egg.

Closely related to the question of distribution of stresses in normal buildings under normal loads is that of the distribution in abnormal buildings under abnormal conditions. The tall building in the high wind offers a case in point. By various meters it is possible to measure wind forces, to take account of blanketing effects, and in general to apply the laws of aerodynamics up to the point of determining how a building is loaded by wind. What then happens to the distribution of the load? Is it entirely cared for by the building frame? Modern technology thinks not! But if not, to what extent is it carried by the filler panels—and how? This is evidently a very complex question and not one to be solved with a pencil, a slide-rule, an assumption or two, and a wet towel around the head. It shrieks for the methods of physics. We need more, much more, research of the wind-tunnel type on big buildings even though the work must be founded on analogy. If this research does reveal, what many now think, that the filler panels are of great importance in transmitting and carrying wind stresses, the windowless building suggested earlier will be even more desirable. Evidently, if physics will put its mind to the problem it is quite possible to visualize vastly different buildings in our cities of the future.

I have reserved for last consideration some of the applications of modern physics which seem to indicate that physics at long last has again become aware of its first child.

The first of these is soil mechanics, which has taken on the dignity of years so quickly it is hard to realize it began little over twelve years ago. The largest part of the world's construction cost is in working the earth; all our structures built to date rest on earth; yet through the centuries the very bottoms of our buildings have been designed on a purely empirical basis. At last we have commenced an attack on this involved problem of the properties of the earth and its behavior on a scientific basis. The first international conference on soil mechanics, held at Harvard University this summer, has confirmed the maturity of the science by the wealth and significance of its papers. Our present knowledge of the physics of soils has permitted us at least to grasp at the essentials controlling earth equilibria. It has made us realize, with some chagrin, how very narrow were the limits of validity of the older

hypotheses, and, with some fear, how several sources of danger exist that have hitherto hardly been suspected.

Quite recently the principles of soil mechanics have been used by José Cuevos in designing the foundations for the National Lottery Building in Mexico City. The soil here is very treacherous. As an extension of a similar earlier design in Albany, Cuevos decided to float the building altogether by excavating a weight of soil exactly equal to the weight of the new building. During excavation frequent observations were made of the level of the soil through a number of subgrade observation points. There was an irregular though continuous rise of the subfoundation during unloading to a maximum of 4 feet. As the excavation was completed the bottom was covered with a flexible flooring of boards carpeted with a waterproof membrane. On this flooring inverted Tee-beams were spaced tightly but so connected that they were flexible enough to move downward with settlement. On the Tee-beams was a rigid substructure of reinforced-concrete trusses on which was a surcharge of gravel sufficient to make the combined weight of all these elements equal to the calculated weight of the building superstructure. It is expected that the surcharged substructure will after a few months bring ground movement to a point of stability at which erection of superstructure may proceed without disturbing the soil equilibrium attained. As the structure is carried up, equal weights of gravel surcharge will be removed. Pure but not simple physics.

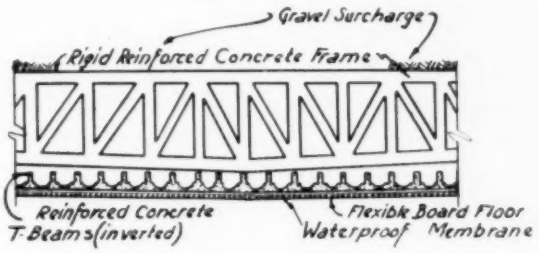


FIG. 2. Diagram of substructure for "floating" the proposed National Lottery Building in Mexico City, designed to allow ground settlement during erection.

Closely related to these studies in earth is the study of dynamic stresses caused by earth movements. Although we have had crude shaking tables, until recently our work in relating shocks to building has been distinctly desultory. If one type of construction withstood an earthquake while the others did not, we built of the former. If more than one type or if no type stood up, we were simply out of luck.

Since the Long Beach tremor, however, there has been a more serious effort to apply the findings of seismology to the building art. The seismologist who has worked faithfully for long without much recognition has been brought out into the daylight. The Coast and Geodetic Survey in collaboration with California universities has done a remarkable job of supervising an extensive program in California of obtaining vibration data and of studying existing buildings. Blake, of that service, has suggested a method of double integration to save the engineer much time in converting accelerograms to data on displacement altitudes and periods. Neumann, also of the service, has developed a mechanical method of carrying out this double integration based on the principle of the torsion pendulum which will reduce the analytical problem to a minimum. Incidentally, no small contribution of the physicist to building may be machines of this type—for example, Bush's differential analyzer and Wilbur's simultaneous-equation machine.

Arthur C. Ruge and Dean Vannevar Bush of M. I. T. have made it possible to develop in the laboratory directly from seismograph records duplicate motions of destructive earthquakes. A shadowgraph is made from an actual seismograph by silhouetting the wavy line representing the quake motion on the periphery of a disk. As the disk revolves, a beam of light operates against its profile to stimulate an electrical analyzing device which in turn controls a valve feeding oil into a piston cylinder. The piston is connected to a shaking platform which, unlike its predecessors, is free to move in any direction. This machine has no limitations as to how irregular an earthquake it can reproduce. Since the motion generated by the machine is known, it is possible to obtain by means of models rather exact analogies with what would happen to a given structure under a given earthquake.

Ruge found in testing a water tank that even two consecutive transient harmonic vibrations,

with an acceleration of 3 percent g and with the ground period about equal to the period of free vibration of the tower, caused a deflection at the tank over three times as great as would have resulted under a static horizontal load of 3 percent of the weight of the tank and contents applied at the tank, which would have been the hypothesis behind the ordinary static method of computation. Inaccuracies of this order in the static method are evidently intolerable if we have any means of knowing more. For this knowledge we must reply upon physics. As a result of this work, Ruge and his confreres have developed a rather radical new design for tanks including the use of springs; so far this has not met with a great deal of favor with those engineers who style themselves practical.

It might as well be admitted here that the practical engineer has something on his side in a question of this sort. There are many problems of resonance, soil conditions, and the like that we still need to know about. The practical designer of a power station, for example, feels that it is dangerous to short-cut through the agency of an incomplete science. He points out that a power plant is a complex structure—that before it can be analyzed the analyst needs to know the magnitude and rate of change of the applied acceleration, the time through which each acceleration value will act, the elastic properties of each path by which acceleration is conducted to the masses of the structure, the damping effect of each such path, and the magnitude of the masses, while the latter is the only one now determinable with precision. He states that academic solutions based on approximations may prove as misleading as the old static theory.

And he is quite right. We have only begun to establish the technique for exhaustive research, often of the variety known as pure, into the questions of earth, of wind, and, most of all, of dynamic as opposed to static stresses. It is no exaggeration to state that there is in this phase of the building industry ample stimulus for many workers for a long time.

But will it be rewarding work? To the pure scientist, of course, for the chase is his interest full as much as the quarry. There are institutions and means for keeping pure research going. But much of the work in the building industry falls under the head of applied research. And here we must face the stubborn fact that he who works on applications of science has not yet been able to apply science successfully to the problem of working while not eating. The bread and butter of the applied scientist is paid for largely by industry, and industry seldom pays for anything on which it sees no possibility of ever realizing a profit. Perhaps the outstanding reason why we have no very serious and coherent applied physics in the building industry is because we have so few corporations large enough and interested enough to pay for the needed work. The materials manufacturers, the only really large units in our industry, work more to improve the properties of their materials than to find new structural uses. This is but natural. New uses would ordinarily postulate more economical uses, and such research might well lead to the consumption of less material, which on the face of it would seem unprofitable. Of course, physics may have its way with these recalcitrants, too. Transfers of precision control from the laboratory to the plant have had almost incalculable impacts. For example, the continuous rolling mill has increased the productive capacity of sheets and tin-mill black plate to more than sixteen million tons per year, yet the 1935 output was only a little over six million tons. There is a natural urge to use this capacity. This is one of the reasons why the steel industry looks with such interest on the housing industry, which, as the steel journals themselves say, offers a market for steel worth fighting for. Research may be on the horizon.

Continually when I speak of the lack of self-interested subsidy for building research I find the suggestion being made that this will come from the prefabricator. Of course, if we had any prefabricator with a real and going business and money in the bank, this might be so. When we come to prefrabrication, I find myself for perhaps the first time this morning on solid instead of seismological ground, and I may assert what is to come with a fair degree of confidence.

It is no pleasure for one who works on the boundaries of the promised land of science to come before a group of men of accomplishment and state that he and all his co-workers in the field of prefabrication have, when all is said and

done, very little in the way of accomplishment to report. I do not propose here to attempt a complete diagnosis of what has been wrong with prefabrication studies. In any event so many have been the discouragements, and so acute, that it is possible to find intelligent people to say that the problem is not one for the scientist or the engineer but purely and simply one for the banker and the sales expert.

But this sort of broad statement has been made time out of mind. The question of finance is, of course, important. In my judgment, however, the prefabrication problem has had altogether too many ministrations from the sales expert already. The philosophy behind Carlyle's "better hat" still endures—our trouble is that we have not got the "better hat."

There has been some accomplishment. I very definitely have in mind the abstract work in the standardized dimensioning of buildings for mass production by the late Albert Farwell Bemis, a thesis that has been clearly stated but has not been applied far enough to have its true test. Serious suggestions, too, have been made by others (there really are more sincere people than charlatans among us). But from beginning to end these suggestions have not been subjected to enough study, enough research, enough dispassionate examination. So I shall make another.

When James Watt invented the steam engine he was not thinking in grandiose terms about improving transportation. He did not care whether some people—no, most people—preferred stage-coaches. It is equally certain that when the Wrights set sail from Kitty Hawk you could have found very few people to get into their contraption. The Wrights did not care, either.

But in prefabrication we are always worrying about what somebody thinks he wants. We have none of us dared face the issue squarely. We have not examined a house to see just what it is that is to be provided. It certainly is not an oil burner or a fireplace or a telephone *per se* that the householder wants. He wants to be sheltered from the elements, he wants to be warm, he wants to see, he wants some degree of sentimental repose, he wants communication with the outside world, and he wants all of these to improve all the time. Recognizing that my analogy is imperfect because of the fact that we have competitors who now produce these things traditionally, none the less I think the greatest mistake we have made and are continuing to make is in not having a well-rounded picture of our objective. Let us be more specific.

What we seek in prefabrication is a method of making the same part over and over again so that it can be mass-produced, rapidly and cheaply assembled, and yet yield a reasonable amount of flexibility in the final product, the house. We may seek it in many ways. To make my point still clearer, let us imagine that you and I have decided that we shall seek to do this by means of a standard panel.

So long as we are building mere boxes with openings these standard panels are easy to design. Even window and door panels offer no serious problem; although they do increase the number of types that we have, still that increase is within reason.

But in that box we now have to place lighting fixtures, switches, a furnace, radiators or registers, stoves, refrigerators and other ganglia and to tie them back with conduits, ducts, wires and myriad other nerves to the spinal cord of the community. Since these nerves cost money, we cannot afford to put them where we are not going to use them. Yet if we put them only in or on designated panels, then these panels too become special; and before we know it we have more special panels than we have standard panels.

In this predicament it might pay us to consider whether these are the right kinds of ganglia and nerves. We want artificial light. Does that mean we must have Mazda bulbs and candelabra and switches and wires? Might we not have a system of illumination that would, just as an example, occupy the top portion of each and every wall panel so that a diffused light would be spread throughout the room? The question is for physics to answer. We want heat. Does that mean radiators and pipes? Can we not develop all our wall panels into radiant panels so that we can afford to put equipment in each? The question is for physics to answer. I am well aware that today's cove lighting or today's methods of heating radiant panels are so expensive as to make the suggestion fantastic. But the fantasy of today is the legend of tomorrow.

The implications are obvious. It may be that prefabrication will arrive only when it dares to look away from convention; when it is concerned not with improving housing or the house but with building a scientifically planned machine to live in. It is evident that no prefabricator will in the near future employ many physicists, much as he needs them. For no prefabricator can afford the necessity. Such a program as this would have to be pursued by some large existing entity with the facilities and the funds to carry on research in the collateral lines that will in the last analysis determine the success or the failure of the prefabricated house. If this does not come to pass, then through slow development along present lines in college and industrial laboratory you, the physicists, will gradually strike the shackles from the prefabricator.

Most of the dramatic accomplishments of physics in the fields of my confreres of this meeting are recent and living. In my field most of them seem old and dead. But there is clear evidence of renascence. As the pure scientist works with greater concentration on the facts of light and sound and heat and electricity, as the applied scientist puts these principles into action with new devices, we shall unquestionably see a burgeoning of physics in the building industry.

In closing, I should like to leave with you these words whose validity is unimpaired by their ardor. They were written by Grosvenor Atterbury, the dean of workers in the field of prefabrication:

"What really interests us most vitally today? Is it the discovery that my umbrella, if projected through space at sufficient velocity, will actually become shorter, until, if Einstein's theory is what it is cracked up to be, it will disappear altogether? Scarcely. I can lose umbrellas fast enough as it is. . . . Now we are spending millions to build 200-inch telescopes to scan the universe and determine whether it is getting measurably smaller or incalculably greater. All of which, in the present state of the realm, seems brilliantly useless, especially when you consider the millions who cannot afford decent homes because none of our great minds has ever been focused on the basic everyday problem of human shelter. Science needs an intelligent board of directors. With a small amount of such brains as are now focused on the speed with which the neutron penetrates the nucleus of the atom, and only 2 or 3 percent of the money now devoted to research into the living conditions at the dawn of history, the cost of the poor man's housing today could be cut in half."*

The challenge of humanity is a challenge that physics may not well ignore.

* Architecture, April (1936), p. 193.

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**J. E. Burchard**

*John Ely Burchard was born in Marshall, Minnesota, December 8, 1898. After attending the University of Minnesota for a short time he left to join the A. E. F. until 1919. In 1923 he received his S.B. from the Massachusetts Institute of Technology and in 1925 received an M.S. in Architecture from the same institution. While carrying on part-time teaching at M. I. T., he joined the Bemis Industries, Inc., first in charge of the laboratory, then as director of research and now as vice president. He is the author of many papers concerned with the improvement and standardization of building practice and an Associate Editor of the Technology Review. In 1933, under joint authorship with the late A. F. Bemis, he wrote "The Evolving House, A History of the Home."*

# Let the *Physicist* Change Your Oil!

By PAUL D. FOOTE

*Executive Vice President*

*Gulf Research & Development Company*

*Pittsburgh, Pennsylvania*

***Here are presented some of the perplexing problems arising in the lubrication of automobile bearings.†***

HERE we have the hard-working industrial physicist contemplating an oil change, Fig. 1. He looks somewhat like an academician and perhaps he is,* for he is dealing with a highly academic subject. His problem involves the basic physical principles of the classical hydrodynamics with just a touch of the occult and possibly a trace of the indeterminacy of the quantum mechanics. As briefly as possible let us attempt to outline a few of the perplexing questions this unfortunate physicist must consider before he can intelligently make any recommendation regarding the lubricant in the crankcase of his motor.

Although the practice of lubricating the bearings of machines by separating the solid surfaces by viscous liquids or plastic solids has probably been universal since machines were first devised, a theoretical interpretation of the action of the lubricant awaited the work of Osborne Reynolds[1] in 1886. And yet the formulation of Reynolds' analysis, which is the foundation of the present theory of thick film lubrication, is based upon a most elementary physical picture.

Thus considering the problem of the full journal bearing shown in Fig. 2, which is at the same time of practical significance and amenable to rigorous treatment, an application of the classical hydrodynamics gives at once the necessary structure of the theory. For observing that the radii of curvature of the moving journal and stationary bearing surfaces are large compared to the film thickness in all cases of practical importance, it is clear that one may justifiably consider any differential element within the lubricating film as if it were moving between two parallel plane surfaces. Recalling then from the classical hydrodynamics that the volume flux of a liquid of viscosity $\mu$, passing between two parallel plane surfaces moving parallel

FIG. 1. A physicist for your oil problems.

* But the probability is small; cf. Jeans, *Dynamical Theory of Gases*, Second Edition, Section 254.

† Presented at the meeting of the Founder Societies of the American Institute of Physics, October 29 to 31, 1936 in New York.

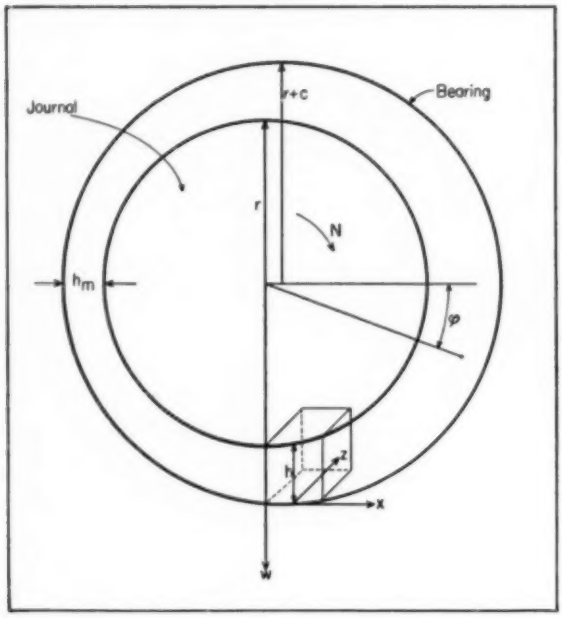


FIG. 2. Diagrammatic representation of a full journal bearing.

to themselves with the relative velocity $U$, and separated by the distance $h$, while subjected to a pressure gradient $dP/dx$, is given by:

$$Q = -\frac{1}{\mu}\frac{dP}{dx}\frac{h^3}{12} + \frac{Uh}{2},$$

it follows at once, from an application of the equation of continuity, that the motion of the liquid film between surfaces separated by a height varying in the $x$ direction and subjected to a variable pressure gradient will be governed by the differential equation:

$$\frac{\partial}{\partial x}\left(\frac{h^3}{12\mu}\frac{\partial P}{\partial x}\right) + \frac{\partial}{\partial z}\left(\frac{h^3}{12\mu}\frac{\partial P}{\partial z}\right) = \frac{U}{2}\frac{dh}{dx}.$$

This is the Reynolds equation underlying the theory of thick film lubrication.

To treat the specific case of the journal bearing, one must impose the appropriate geometrical definition of the system and the corresponding boundary conditions. The former are contained in the statement that the film thickness $h$ is that of the eccentric annulus lying between the two cylindrical boundary surfaces. This can be easily defined in terms of the displacement of the center of the journal and the radii of the journal and bearing. The boundary conditions are, in the case of the full journal bearing, the periodicity of the pressure as one completes the angular distance of $2\pi$ in $\Phi$, and the requirement that the pressure assume the atmospheric value at the ends of the bearing, if of finite width, or that it be independent of the axial coordinate if of infinite width. The latter case under the assumptions of liquid incompressibility, absence of turbulence, and independence of viscosity of pressure and rate of shear, was first satisfactorily treated by Sommerfeld[2] in his classical paper of 1904, in which the analysis for the partial journal bearing, namely, that consisting of an arc of a circle, was also fully discussed for an infinite bearing width.

Once the pressure distribution in the lubricating film has been found by the solution of Reynolds' equation, it is evidently a simple matter to calculate the resultant upward thrust of the fluid film upon the journal, which obviously must equal the bearing load, and the resultant tangential traction moment upon the journal which must equal the torque moment externally applied to keep it in motion. These will, of course, depend upon the liquid viscosity, the journal speed, and the shift of the journal axis or, what is of greater interest from a practical point of view, on the ratio of the minimum film thickness, $h_m$, to the radial clearance, $c$, when the two cylindrical surfaces are concentric. The relation between the external moment and the bearing load may be most conveniently expressed in terms of the coefficient of friction, which is defined as the ratio of the tangential

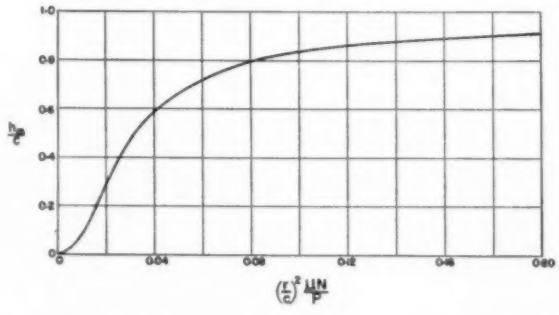


FIG. 3. Theoretical variation of the minimum film thickness, $h_m$, in a full journal bearing with the lubricant viscosity, $\mu$, the journal speed $N$ (r.p.m.), and bearing load $P$ (per unit projected area). $r$ = journal radius; $c$ = radial clearance between journal and bearing.

frictional force on the journal to the bearing load. These relations are summarized by the curves of Figs. 3 and 4, which indicate that, as can also be proved by dimensional analysis, these ratios are functions only of the dimensionless Sommerfeld variable $(r/c)^2\mu N/P$, where $r$ is the journal radius, $c$ the radial clearance, $N$ the journal speed in r.p.m. and $P$ the bearing load per unit projected area, the curves in this form having been first published by Hersey.[3]

From Fig. 3 it is clear that the minimum film thickness $h_m$ for a given clearance increases monotonically with increasing liquid viscosity and journal speed and decreasing load. Hence the journal will rise and shift from an effectively solid contact with the bearing at very low speeds or extremely high pressures until it becomes practically concentric with the bearing as the speed is increased or the load lessened. One thus sees already an indication of the fact that has only recently begun to be generally accepted, namely, that the major part of bearing wear is effected during the starting of the journal shaft and the build-up of its speed until the minimum clearance appreciably exceeds the roughness irregularities in the journal and bearing surfaces, and during the slowing down of the engine when the motor is turned off.

The physical reason for this decrease of the journal eccentricity with increasing values of $\mu N/P$ lies, of course, in the fact that as either $\mu$ or $N$ increases, the total shearing stresses and the fluid pressures in the film likewise tend to increase, thus necessitating a smaller wedging of the film to create the resultant upward pressure component required to support the load $P$. On the other hand, when $P$ is decreased, while $\mu N$ is fixed, a smaller upward component of the fluid pressures will suffice to carry the load, which can again be derived from a smaller eccentricity.

While the life of the bearing itself is closely related to the minimum film thickness, the efficiency of the machine as a whole will be more directly determined by the coefficient of friction $f$, plotted in Fig. 4. Here the interesting and extremely important behavior is disclosed in which the coefficient first decreases approximately linearly as the dimensionless variable $\mu N/P$ is decreased from large values, then flattens to form a minimum, and finally rises as the coefficient of friction axis is approached. The immediate implication of this result is, of course, that the most efficient performance of the machine will be attained at such speeds and loads and with such a lubricant as will make the product $(r/c)^2\mu N/P$ have the value 0.0211, at which the coefficient of friction is a minimum. While the minimum shown in Fig. 4 is only 6 percent below the coefficient corresponding to zero velocity, and hence the gain in attaining the minimum value would not warrant any particular effort, we shall see later that in practical tests the rise above the minimum point as the variable $\mu N/P$ is decreased is so very rapid that it has become customary to consider the ranges of valuesof $\mu N/P$ to the right and left of the minimal point as representing two distinct types of lubrication.

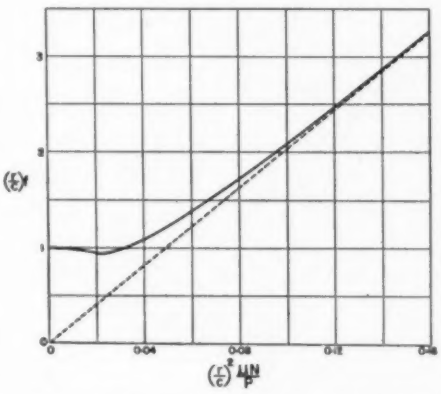


FIG. 4. Theoretical variation of the friction coefficient, $f$, in a full journal bearing.

Here, too, it should be noted that a simple physical interpretation underlies this rather complex behavior. At high values of $\mu N/P$, the journal and bearing tend to become concentric, for which case an elementary analysis shows that the relation between $(r/c)f$ and $(r/c)^2(\mu N/P)$ should be represented by a straight line through the origin with slope $2\pi^2$, which is indeed approached asymptotically by the curve of Fig. 4. However, when $\mu N/P$ is decreased, the rapidly growing eccentricities and sharply decreasing minimum film thicknesses will more than counterbalance the decreasing journal velocity (for fixed $\mu/P$) and thus give rise to increasing values of the tangential shearing stresses and hence larger coefficients of friction. These opposing effects will obviously result in a minimal value for the coefficient of friction between the extremes of very low and very high values of $\mu N/P$.

From the discussion so far presented the only physical property of the lubricant which enters into the hydrodynamic theory of lubrication is viscosity. It is, therefore, appropriate that we devote some attention to this phase of the subject. Unfortunately, physical theory is not yet capable of providing a quantitative treatment of an assembly of molecules in the liquid phase with respect to such macroscopic interactions as give rise to the forces of viscous friction. When it is realized that in the very much simpler problem of predicting the viscosity of gaseous molecular ensembles, the labor of the necessary calculations is so involved that they have been carried through for only two or three specific cases, it is not surprising that the corresponding program for the accurate calculation of the absolute values of liquid viscosities must be almost impossible of execution. On the other hand, a little consideration will show that it is not only a difference in degree of complexity but also one in the nature of the physical picture which distinguishes the problems of explaining the viscosity of liquids and that of gases.

Thus the fact that the viscosities of liquids universally decrease with increasing temperature, whereas those of gases increase, implies that a fundamentally different mechanism is involved. Another significant difference lies between the effective mean free paths of the molecules in the gaseous and liquid states. While at normal pressures and temperatures the mean free path of the molecule in a gas may be some 25 times as great as the average separation between the molecules, the phenomenon of diffusion, as well as probability considerations, indicate that molecules in a liquid may make as many as 100 collisions before their resultant displacement in a given direction will equal the average molecular separation. This latter inference is drawn from a picture in which the liquid molecules are conceived to be in states of quasi-rigid vibration with frequencies comparable to those in the solid state and with slowly drifting equilibrium positions. It is confirmed by both x-ray evidence and recent studies of the dielectric behavior of liquids which indicate that the liquid state may be more closely described as a solid of a high degree of macroscopic disorder and hence negligible rigidity rather than a mere condensation of a gaseous ensemble which has thereby lost its elasticity. The momentum transfers involved in the shearing stresses created by the velocity gradients in a liquid may then be attributed to momentary molecular unions occurring at the extremes of the molecular librations. While this picture has not been so refined as to yield a prediction of the absolute values of the viscosities of specific liquids, it is both sufficiently inclusive of the fundamental physical factors involved and inherently simple as to lead to a formula for the viscosity that reproduces quite closely the viscosity characteristics of a large class of liquids, and especially those associated with temperature variations. This formula, first derived by Andrade[4] from such a physical picture, is:

$$\mu v^{1/3} = A e^{c/vT},$$

$\mu$ being the viscosity at the temperature $T$, $v$ the specific volume, and $A$ and $c$ are constants which have not been quantitatively derived from the theory, but the latter of which may be shown to be closely related to the mutual potential energy between the molecules of the liquid.

As long as the constant $A$ cannot be derived from the theory itself it is, of course, impossible to predict the absolute values of the viscosity by this formula even if the exact value of the constant $c$ were known. However, from the point of view of automotive lubrication the variation of viscosity with the temperature is of considerable importance. Under severe driving conditions the lubricant in an automotive engine may undergo local temperature variations of 200°C.

One criterion of a satisfactory lubricant, therefore, must be that its viscosity both at the low temperature when the engine is started and at the high temperatures developed after the normal running speed has been attained, be such that neither the power consumed nor the bearing and journal wear will be excessive at both limits of the temperature range. As a result of the limited power capacity of the starting motor, it is clear that the viscosity of the lubricant at the low temperature of the atmosphere must not overtax the capacity of the starting motor to accelerate the speed of the engine until ignition is effected, i.e., to about

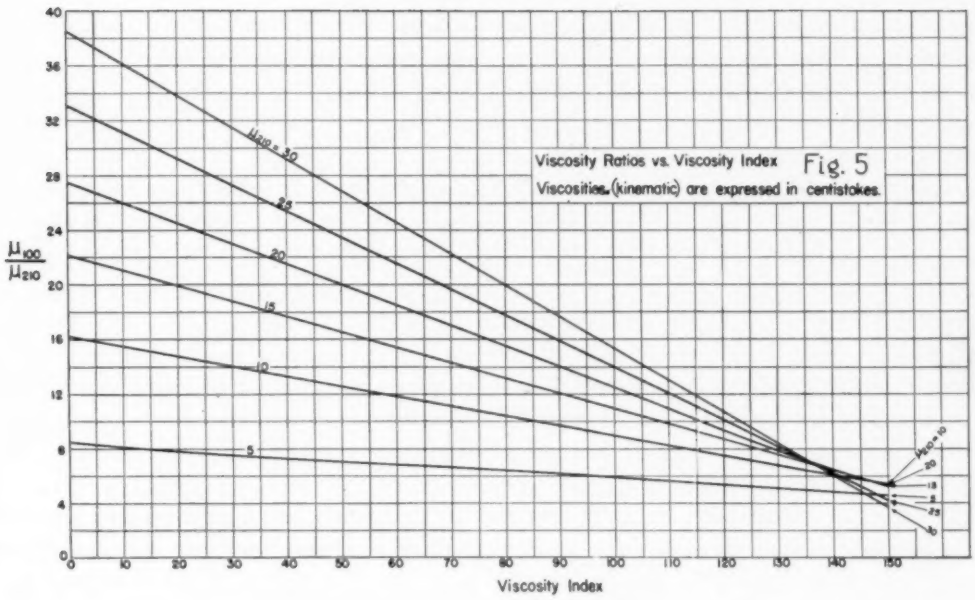


FIG. 5.

50 r.p.m. At the same time it must be high enough so that the film thicknesses during the low speeds of starting remain sufficiently large to minimize the danger of metallic contact and possible scoring or seizing of the surfaces. Once this step of starting has passed, the latter requirement must again be met. However, it now takes the form that the viscosity should not fall with the rise in temperature to such a low value that in spite of the increased journal speed, the product of the speed and viscosity will again become so low that the minimum film thicknesses once more fall to such small values as to allow abrasion by dirt* and grit, or to bring the metallic surfaces into effective contact, thus leading to the associated danger of "burning out" the bearing. While the lowered viscosity at the higher running temperature will decrease the power losses, and hence apparently give a more efficient operation of the machine, the objections to decreased film thicknesses may more than offset the favorable effects, so as to give a lubricant of smaller temperature coefficient a higher resultant rating than one with a high coefficient. In fact, it has become the practice of the industry to rate the viscosity characteristics of lubricating oils by their "viscosity index," which is really nothing more than an arbitrary expression for the viscosity ratio between the temperatures of 100° and 210°F. The relation of this viscosity index to the actual ratios of the viscosities at 100° and 210°F is shown in Fig. 5. Although, as this figure shows, the viscosity index highly exaggerates the relative ratings of oils of low viscosity at 210°F, the viscosity ratios of which differ but slightly, a considerable part of present day automotive oil promotion is based upon this arbitrary scale.

As some degree of control on the viscosity variations of a lubricant over the range of temperatures to which it is normally subjected is desirable, the question arises as to the most effective means of attaining such limitations. While this is admittedly an unsolved problem, some indications are suggested by the known viscosity characteristics of commercial lubricants. Thus from the general observation of Duff[5] that all the formulas that have been proposed for describing the viscosity variations of liquids with temperature are integrals of the differential equation

$$\frac{1}{\mu}\frac{d\mu}{dT}=\frac{1}{\alpha+\beta T+\gamma T^2},$$

it follows that among a given class of similar lubricants—those having approximately equal values of $\alpha$, $\beta$, $\gamma$, respectively—the oils with the smaller absolute viscosities at a given temperature will have the smaller temperature coefficients. That is, the "heavier" lubricants in a certain class show the greater range of variation of viscosity. To the extent that the viscosity

* Road dust is an appreciable factor in bearing wear.

index does give a physical classification of similar lubricants, this implication of the above equation is clearly confirmed by the curves of Fig. 5.

A more physical suggestion follows from Andrade's formula, which corresponds to $\alpha=\beta=0$, $\gamma=-1/c$ in Duff's equation. From the already mentioned correlation between Andrade's constant $c$ and the mutual potential energy between the molecules of the liquid, it is seen that symmetrical molecules with small external fields should have small temperature coefficients. This prediction is strikingly confirmed by the metallic liquids such as mercury and gallium,[6] the latter of which suffers a viscosity variation of only 3.3 fold between its melting point, 30°C, and 1150°C. This may be contrasted with the behavior shown in Fig. 5 of the typical mineral lubricating oils, which, over the very much smaller range of 100° to 210°F, show variations of viscosity of the order of 10–25 fold.

Unfortunately, however, the molecules of mineral lubricating oils are not only much more complex than the monatomic molecules of metallic liquids, but such oils are composite solutions of many types of molecule of unknown detailed structure. Hence it is very difficult to apply to them the Andrade theory so as to predict their relative temperature coefficients except by means of the rough classifications into heavy and light oils mentioned above. Furthermore, it is practically impossible to anticipate on the basis of physical reasoning the results of attempts to modify artificially their viscosity temperature coefficients. Present commercial practice is, therefore, based upon the method of blending oils of known and different viscosity characteristics so as to obtain an oil of intermediate properties. While there is nothing physically surprising in the success of the blending process, the reasons for the effectiveness of very small additions of high molecular weight* and long chain compounds still require considerable clarification. A rather interesting interpretation suggested by Lewis and Squires[7] is based upon the Staudinger[8] concept that the long chain compounds form "molecular colloids" when dissolved in organic solvents, the resultant viscosity of which may be expressed by an Einstein equation of the form:

$$\mu=\mu_0(1+\alpha v),$$

$\mu_0$ being the viscosity of the solvent, $v$ the volume concentration of the solute, and $\alpha$ is a constant depending on the nature of the dispersed phase. Neglecting the variations of $v$ and $\alpha$ with the temperature, it would follow from this relation that although the absolute viscosity of the solution will exceed that of the solvent, the ratio of the viscosities at any two temperatures will be no greater than that of the solvent. Reference to Fig. 5 shows at once that the solution has a higher viscosity index than the original solvent. On the other hand, it is clear that the actual temperature coefficient is increased by the addition of the solute throughout the whole temperature range. Although this picture explains some of the broad features of the problem of increasing viscosity index by the addition of small concentrations of high molecular weight compounds, it must be admitted that in its present form it is inadequate as regards many important details. In the development of a thorough understanding of this interpretation or of other explanations lies indeed a most important field of research for both the theoretical chemist and physicist.

Up to the present point in this discussion one might question why mineral oil should be selected for a motor lubricant. Molasses, sugar solutions, gelatin, casein, gums and soaps, fatty oils from animal and vegetable sources, special organic liquids, such as glycerin and the poly-glycols, can be prepared with suitable viscosities and satisfactory temperature coefficients. Most of these substitutes however are impractical because of their instability at the high temperatures involved. The oil in the crankcase of an engine under heavy duty will reach 140°C, the bearing surfaces 150° to 200°C, and at the upper piston ring grooves and the underside of the piston crown, temperatures may exceed 250°C. The temperatures which the oil in the bearings encounters are only partly due to the heat dissipation of frictional forces and arise to a considerable extent in heat conduction and radiation losses from the explosion chamber. A primary

* In the aluminum chloride process for the manufacture of lubricating oil, such high molecular weight compounds are synthesized, and are partly responsible for the high viscosity index.

function of the lubricating oil is therefore its capacity as a coolant, and by rapid circulation as much heat as is possible, within the limits of economic feasibility for engine design, must be conducted away from the bearing and eventually dissipated to the atmosphere.

The trend of the automotive industry toward lower weight of engine per horsepower and higher engine speeds increases this difficulty, and each year motor oils are required to withstand greater operating temperatures. Furthermore the crankcase ventilator pulls from 3 to 25 cubic feet of air through the oil every minute. This creates a splendid condition for mechanical removal of oil as fog or mist, and for evaporation which must be minimized to a reasonable extent in a satisfactory lubricant; but especially it favors deterioration by oxidation. In fact a ventilated automobile engine is more or less a replica of a plant for the manufacture of blown asphalt.

The oxidation of lubricating oil manifests itself by an increase in viscosity, precipitation of sludge, the development of organic acidity, and other undesirable features. From a study of the kinetics of oxygen absorption by oil, the phenomenon is found to belong to the class of autocatalytic chain reactions.

The theory of chain reactions was formulated originally by Bodenstein[9] in 1913 principally in order to explain the failure of the Einstein law of photochemical equivalence in the case of photochemical reactions having a quantum yield greater than one. In 1923 it was first applied to thermal reactions by Christiansen and Kramers[10] in an attempt to account for the abnormally high reaction rates of certain unimolecular reactions. Recently the theory has been greatly elaborated, chiefly by Semenoff[11] and Hinshelwood.[12]

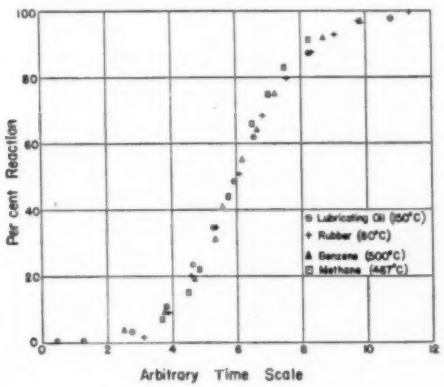


FIG. 6. Oxidation of various hydrocarbons as a function of time—adjusted so that $t=6$ corresponds to a 50 percent completion of the reaction.

According to the theory of chain reactions, chemical reactions take place in a series of elementary steps. For example, the reaction

$$A_2+B_2\rightarrow 2AB$$

might be supposed to take place in the following fashion:

(1) $A_2\rightarrow A_2'$,
(2) $A_2'+B_2\rightarrow AB+AB'$,
(3) $AB'+A_2\rightarrow AB+A_2'$.

$A_2'$ is an activated molecule having an energy content corresponding to a point somewhere in the right tail of the Maxwell-Boltzmann distribution function. It reacts with the molecule $B_2$ to yield products containing not only the energy of activation but also the heat of reaction. If this total energy is distributed in such a manner that $AB'$ has a sufficiently high energy content, it may then collide with and activate another molecule of the original reactant $A_2$. Reactions (2) and (3) are said to constitute a chain and it is evident that, provided the energy transfer efficiency is high, a great many molecules of product can be formed for every molecule of $A_2$ activated. The average chain length of the chain reaction is the number of times the cycle (2)–(3) is repeated, on the average, before the chain is broken, for example by energy degradation of $AB'$ or $A_2'$ by collisions with the walls or with other inert molecules. If both the products of (2) are activated molecules, $AB'$, then both can give rise to activated $A_2'$ and the chain is said to be branched.

Semenoff has developed expressions for the rate of growth and decay of the chains as a function of time. In the case of the majority of hydrocarbons, during the initial stage of the oxidation the reaction rate increases exponentially, reaches a maximum value at half-time and then decreases exponentially. The whole course of the reaction can be represented by a universal function (essentially the logistic function) applicable to all reactions of the same general type. It has been found that the oxidation of highly

refined lubricating oil can be also accurately expressed by the same function. In Fig. 6 are shown the results, as collated by Dr. Montgomery of this laboratory, on the oxidation of methane and benzene (taken from Semenoff[11]), rubber (results of Kohman[13] recalculated) and lubricating oil, plotted according to Semenoff's expression for the complete reaction. The striking agreement among the four sets of data indicates the similarity of mechanism involved.

In accord with the chain mechanisms proposed for the oxidation of other hydrocarbons it is therefore possible to set up a similar chain mechanism for lubricating oil oxidation. Such a reaction scheme contains active "peroxidation" and "hydroxylation" compounds and other hypothetical intermediates which the chemist usually includes in a reaction mechanism but has never been able to isolate.

Perhaps a sounder physical attitude toward the chain reaction mechanism is to regard the process primarily from the energy transfer standpoint. The energy content of the reaction intermediates or chain carriers is, in the last analysis, the important thing. The separate chemical existence of reaction intermediates is probably limited to the extremely short time spent by a reaction complex in a shallow trough on the potential energy surface as described by Eyring and Polanyi.[14]

Small traces of certain complicated chemicals known as inhibitors can be introduced into an oil to reduce its susceptibility to oxidation. In fact many crude oils contain natural inhibitors, usually in the form of sulfur, nitrogen or oxygen organic compounds, and if some of these are carefully preserved during the refining process, the finished product may possess outstanding stability. Inhibitors, in general, greatly decrease the chain length by causing an increase in the probability of chain-breaking. This might be interpreted by assuming that inhibitors have a high efficiency for absorbing the activation energy of reactive intermediates, distributing it through a large number of internal degrees of freedom (to prevent localization and subsequent loss of energy in toto), and finally dissipating it in much smaller quanta by collisions. In partial support of this view is the fact that the reaction rate in most cases varies with the inhibitor concentration in exactly the same way as intensity of fluorescence varies with the pressure of foreign gas. It is also interesting to note that fluorescence of oils gradually disappears during aging, indicating, perhaps, that the intermediate oxidation products can quench the fluorescence of activated oil molecules, possibly becoming activated themselves.

It must be emphasized that oxidation of lubricating oils may proceed in various directions as far as the practical results are concerned. Inhibitors are usually specifics, designed to suppress a particular type of chain reaction, and actually may be accelerants for other types of chain reaction. One inhibitor may stabilize an oil against color change but at the same time may accelerate the formation of acidity. Another inhibitor may retard the development of acidity while increasing sludge formation.

An interesting example of the effect of an inhibitor is illustrated by the data in Table I, obtained by Dr. Kennedy of this laboratory. To an S.A.E. 20 oil which had been so drastically refined that many of the natural inhibitors were destroyed, was added 0.5 percent of a certain type of ester. The uninhibited and inhibited oils were compared in the Underwood test machine in the presence of copper-lead and cadmium-silver bearings, which act as accelerants for the oxidation reaction. The inhibited oil shows no corrosive action and negligible viscosity increase.

Our discussion thus far of the problem of automotive lubrication might give the impression that it consists of nothing more than a particular application of the classical hydrodynamics, together with the development of an oil which

TABLE I. *Data with Underwood test machine.*

| | Refined Oil | Refined Oil Plus Inhibitor |
|---|---|---|
| Average loss of weight of Cu-Pb Bearings for 12 hours | 0.1827 g | −0.0123 g |
| Average loss of weight of Cu-Pb Bearings for 22 hours | 0.4796 | 0.0019 |
| Average loss of weight of Cd-Ag Bearings for 12 hours | 1.7532 | −0.0054 |
| Average loss of weight of Cd-Ag Bearings for 22 hours | 1.8068 | −0.0004 |
| Viscosity, S. S. 100°F | 998. | 272. |
| % Increase Viscosity at 100°F | 290. | 0.6 |
| Viscosity, S. S. at 210°F | 89.3 | 52.1 |
| % Increase Viscosity at 210°F | 75. | 1.9 |
| Viscosity Index | 99. | 109. |
| Carbon Residue | 4.33 | 0.43 |
| Neutralization No. | 7.6 | 0.57 |
| Sludge, % | 2.30 | 0.04 |
| Color | Black | 7+ (Dil.) |

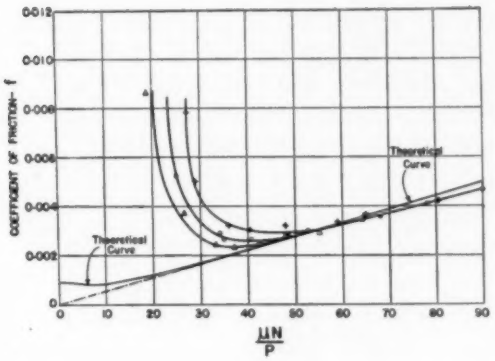


FIG. 7. Comparison between the theoretical friction coefficient for a full journal bearing of infinite length and some typical experimental tests, as obtained by: D. P. Barnard, H. M. Myers, and H. O. Forrest, Ind. Eng. Chem. **16**, 347 (1924) with a steel journal and bronze bearing 2″ long and 1″ inside bearing diameter, with $r/c=1150$, and $P=71$ lb./in.$^2$. The +, 0 and △ refer to different lubricants.

will have high chemical stability and a limited range of variation in viscosity between 0° and 250°F. Unfortunately, however, matters are not so simple.

Thus, on comparing the theoretical data for the friction coefficient shown in Fig. 4 with some typical results from actual tests of full journal bearings one obtains the curves illustrated by Fig. 7. An immediate inspection shows that the differences between the observed results and those predicted theoretically are even more striking than their similarities. Among those differences, however, the ones of particular interest for our discussion are the very sharp rise in friction coefficient after passing the minimum, as contrasted with the extremely slow rise of the theoretical curve, and the spreading of the curves near the minimum point for different types of lubricant, whereas the theoretical curve should in principle apply universally for all lubricants, once their viscosities have been properly taken into account in the specification of $\mu N/P$.

There are several other features of these curves that merit considerable attention, although it is not necessary to dwell at length upon them here. For example, the asymptotic approach of the observed data for high values of $\mu N/P$ to a line which does not pass through the origin, may be contrasted with the theoretical prediction of an asymptotic approach to one that does pass through the origin. One should also note the discrepancy between the absolute position of the minimum of the observed data and that of the theoretical curve both with respect to the Sommerfeld variable and the value of the friction coefficient. Moreover, the fact that the numerical values of these discrepancies are known to depend upon the particular nature of the journal and bearing surfaces and upon the history of the journal and bearing combination, that is the extent to which they have been run in to smooth out the surfaces, must evidently be subjected to physical interpretation in a complete theory of the problem. In fact, it has been found that the position of the minima of the curves can be shifted over a wide range from its position for the very first runs of a particular journal and bearing to those after they have been run together for some time.[15] Finally, a complete theory of journal and bearing performance must explain why various experimenters have found different types of variation of the friction coefficient with the load. For some have found that it is a function of the variable $\mu N/P$, others that $\mu N/\sqrt{P}$ gives the better representation of the data, and still others that the friction coefficient is for practical purposes entirely independent of the load, although dimensional analysis unambiguously shows that the ratio $\mu N/P$ is the only quantity involving $\mu$, $N$, and $P$ that can have physical significance. None of these questions can be dismissed simply by the remark that they arise from errors in experimental tests or that the tests have been made on bearings of finite width, with side leakage, while the theoretical predictions presuppose a bearing of infinite width, although it is true that this latter difference will be of importance in determining the exact numerical magnitudes to be obtained by empirical tests. However, it would carry us too far afield to discuss these discrepancies further. Indeed, with regard to the significant physical features of the problem which arise when small values of $\mu N/P$ are considered, it is sufficient to discuss only the

two facts previously mentioned, namely the sharp rise in the experimental curves and their spread beyond the minimum for different lubricants. This behavior of the friction curves for small values of $\mu N/P$ is so radically different from that for large values that it has become customary to refer to the conditions of lubrication where $\mu N/P$ is less or greater than that giving the minimal coefficient of friction as those in "thin film" and "thick film" lubrication respectively, since obviously the minimal film thicknesses will be smaller in the first range than in the second. In terms of this distinction we shall now consider in more detail the problem of thin film lubrication.

We have already suggested that the physical reason for the existence of a minimum in the friction coefficient *versus* $\mu N/P$ curve lies essentially in the sharp fall of the minimum film thickness as $\mu N/P$ is decreased and a consequent rise in the shearing stresses. However, this effect of the geometry of the lubricating film is just the feature that is taken into account by the Sommerfeld theory, as contrasted with the original Petroff assumption that the journal always stays concentric with the bearing, and that leads to a curve of friction coefficient *versus* $\mu N/P$, which is the straight line passing through the origin. What new features then come into play and give rise to an additional contribution to the friction losses thus leading to the much sharper increase and the higher absolute values of the friction coefficient than predicted theoretically?

ONE immediate explanation might be that the viscosity of the lubricant under such conditions where $\mu N/P$ is small has abnormally high values. This assumption might be given some plausibility by the remark that for the extremely thin films developed when $\mu N/P$ becomes sufficiently small, the lubricant will no longer maintain its normal bulk viscosity, but will assume, rather, some degree of rigidity such as is possessed by greases or quasi-crystalline liquids. This view has been advocated in many quarters as possessing definite physical reality. For example, x-ray measurements of the structure of films of long chain hydrocarbon liquids upon solid surfaces have been interpreted as indicating a crystalline structure of the liquid film extending beyond the solid surfaces for many molecular layers.[16] This conclusion has been extrapolated to the case where the liquid film is moving under shearing stresses past the metallic solid surface of a bearing. In particular, it has been supposed that the forces due to the metallic lattice extend for appreciable distances into the liquid film, and by some propagating mechanism exert an orienting force and a tendency towards the crystallization of the liquid for distances beyond the metallic surface including tens of molecules.[17] Further substantiation of this picture has been claimed in certain experiments on the flow of liquids through fine capillaries in which plugging effects developed after prolonged flow, thus indicating to these investigators that a quasi-rigid film was being formed from the liquid bulk at the walls of the capillaries.[18]

Unfortunately, however, this invitingly simple explanation does not withstand close scrutiny. Thus using the Sommerfeld theory for the order of magnitude of the actual minimum film thickness that would correspond to the region where the rapid rise in friction coefficient occurs, it is readily found that for radial clearance ratios of the order of 1000, and journal radius of the order of 1 inch, the minimum film thickness will not be appreciably less than about 5000A or about 100 molecules thick even if the molecules are 50A in length. Now the work of Langmuir[19] and Blodgett[20] has shown that the orientation of molecules on an adsorbing surface extends over only a very small number of molecular layers unless the solid surface is deliberately coated with a series of monomolecular layers under a narrow range of and carefully controlled conditions. And even if one grants the validity of the previously mentioned work showing the crystalline character of thick liquid films upon solid surfaces, it does not appear likely that such orientations will persist under the high shearing stresses to which the films are subjected in the journal-bearing. Indeed, it is not necessary to express this statement as a mere opinion, since the very precise work of Bulkley,[21] who repeated the experiments on extremely fine capillaries of internal radii as small as 5.6$\mu$ with both nonpolar and polar liquids, has shown that when the

liquids are carefully prefiltered there is neither plugging nor any other manifestation of a change in the viscous bulk property of the liquid that extends from the surface as far as 200A. Equivalent results have also been obtained by Bastow and Bowden[22] on the motion of both polar and nonpolar liquids in extremely thin films between parallel plates, these liquids being found to behave as perfect fluids even when cooled to within 0.1°C of their freezing points. While these results show definitely that insofar as a continuous liquid film is maintained with thicknesses not appreciably less than those determined by the eccentricity of the journal shaft, the lubricant must behave strictly as a normal liquid, one may note that this conclusion is also that which would be anticipated from purely theoretical arguments. For unless new types of force are invoked, it is difficult to understand how such long range effects required by the suggestion of the change in bulk viscosity over distances extending through 1000A can arise. Indeed, it would be necessary to assume for the liquid phase the action of cooperative forces such as give rise to the sharp melting point of crystalline bodies or the high internal fields of ferromagnetics, an assumption which can scarcely be accepted unless confirmed by independent means.

On the other hand, it must be admitted that a clear cut quantitative explanation of the sharp rise of the friction coefficient in the region of thin film lubrication is not available. What does appear to be perhaps the most reasonable interpretation is that the high friction coefficients are caused by local metallic contacts between the journal and bearing surfaces at the natural projections and random elevations left on such surfaces even after careful machining. The well-known fact that machined or even polished metallic surfaces are seldom plane to an accuracy even as high as $10^{-5}$ inches, alone would lead one to anticipate that when the minimum film thicknesses become of this order of magnitude, effective metallic contact ensues. That such surface irregularities play a significant role in determining the coefficient of friction in the thin film region is further evidenced by the previously mentioned fact that the friction may be very markedly reduced by the running-in of the journal and bearing, which, of course, means a polishing of the surfaces during the running-in process. Further evidence lies in the observation reported by Linsley[23] that the critical seizing pressures of journal bearings are of the order of 100 times as great as those which give the first metallic contact between the journal and bearing, as found by electrical resistance measurements of the oil film between the journal and bearing.

THESE various considerations seem to lead unambiguously to the picture that, in comparison with the minimum film thicknesses occurring during the condition of thin film lubrication, both the journal and bearings must be considered as rough and corrugated surfaces, the maximum projections of which may actually come into effective metallic contact even though the theoretical film thicknesses may contain hundreds of molecules. That the frictional forces created by the relative motion of such surfaces should be much larger than those predicted on the assumption that the surfaces are strictly smooth would be an immediate conclusion. The situation is much the same as if one were to compute for plane parallel plates the pressure drop for the flow of a liquid between two parallel corrugated surfaces in which the separation between the plates is only several times as great as the heights of the corrugations, and expect the experimental measurements to confirm quantitatively the computations.

The tendency for the effective metallic contact to develop even before the surface projections of the journal engage those of the bearings under strictly ideal conditions will, in practical tests, be accentuated by the fact that it is extremely difficult to avoid some degree of oscillation of the journal about its axis. While this may be of little significance in the region of thick film lubrication, it is evident that such effects will become increasingly important as the minimum film thickness falls to the values characteristic of the region of thin film lubrication.

Once the journal and bearing surfaces come into effective contact through the engagement of their surface projections, it is clear that the lubricant film will suffer a rupture. Since the closure of the rupture and the reestablishment

of a continuous film will require a finite time, there will exist on the average about each local point of film rupture a definite time interval when the surfaces are separated only by the adsorbed layers of the lubricant. This effect will also tend to aggravate the imperfection in the lubrication and hence to accentuate the value of the friction coefficient. Of course, if the inflow pressure of the lubricant is not sufficiently high the film may be partly broken even before effective metallic contact is established, because of the negative pressures that are inherently characteristic of the fluid motion in an eccentric annulus. However, from a practical point of view, this situation is remedied by imposing a forced feed upon the lubrication system, which maintains a positive pressure over the whole of the fluid film.

From the nature of this descriptive picture of the actual mechanism of lubrication in the thin film region, it is clear that a quantitative development and hence a numerical test of it by comparison with the empirical data is extremely difficult. Admittedly its status must remain largely that of a hypothesis until it can be formulated in a quantitative manner so as to provide numerical predictions. On the other hand, aside from its plausibility and the lack of serious difficulties in its fundamental elements, it appears to provide an explanation for the other fundamental feature of thin film lubrication performance, namely the differences in the coefficient of friction observed for different lubricants. Since, as already mentioned, the hydrodynamic theory suggests that only the viscosity of the lubricant will affect the coefficient of friction, and furthermore that it is completely taken into account by using the viscosity of the lubricant at the temperature and pressure of the film in the specification of the variable $\mu N/P$, it has been widely claimed that in the region of thin film lubrication a new property of the lubricant must enter the problem. This new property has been named the "oiliness" of the lubricant, the oiliness being considered to be higher for one lubricant than for another when the coefficient of friction in a given test machine for that oil, is less than that for the other for the same values of $\mu N/P$.[24]

Here again we must pass over the question as to whether the viscosities used in the plotting of $\mu N/P$ have been appropriate to the true film temperature, since in the actual tests it is almost universally the bearing temperature which is measured. Rather, we shall suppose that even if the correct viscosities were used there would still be some spread in the curves. Granting this, then, must we necessarily conclude that the differences in the absolute values of friction coefficient is a manifestation of a new bulk property of lubricants? Obviously on the picture that the region of thin film lubrication everywhere involves a complete separation of the metallic surfaces by films of the thickness corresponding to the ideal hydrodynamic theory, the oiliness of the lubricant would have to be considered as a new bulk property of the liquid. This would, of course, be difficult to reconcile with the fact that such a property has eluded detection in all the manifold investigations of the behavior of liquids under an extreme variety of conditions, excepting only such as obtain in the film of a lubricant between journals and bearings operating under the so-called thin film conditions. While one could scarcely dismiss this interpretation merely on the basis of the fact that it involves a previously and otherwise undetected characteristic of liquids, it is nevertheless appropriate that other modes of interpretation be explored before this path of easiest escape is accepted.

CONSIDERING, then, other explanations for this phenomenon of the variation in the coefficients of friction among different lubricants with the same values of $\mu N/P$, it is not difficult to see that the picture suggested above to explain the sharp rise of the coefficient of friction in the region of thin film lubrication will also lead to a reasonable interpretation of the property of oiliness. For supposing again that the thin film is continuously being subjected to the microscopic irregularities in the metallic surfaces, with projections which may well engage long before the theoretical film thicknesses have been reduced to only several molecular layers, it is clear that such a film will suffer an intermittent succession of ruptures and local extreme pressures during the course of the operation of the machine. The resulting friction between the two surfaces will obvi-

ously depend upon the degree to which the film may, on the average, be considered to be unbroken so as to avoid metallic engagement of the surface projections. Variations of lubricants in their capacity to resist rupture and in that of recreation of the continuous film will then be reflected in variations of the resulting coefficient of friction.

A GRAPHICAL description of the tendency of a film to rupture is given by the term "film strength" which, while difficult to define quantitatively, nevertheless does suggest the fact that metallic contact even at the surface projections could be avoided if the resistance of the film to rupture could be made arbitrarily high, that is, if the film strength were indefinitely large. Of course, the assignment of a name to the effect does not go very deeply into its interpretation, and indeed an entirely satisfactory physical description of the process of rupturing a film has not yet been developed. However, it is not unlikely that what is here involved is again largely a matter of the bulk viscosity of the liquid, and perhaps ultimately of its cohesive strength. For, if the normal viscosity of the film were sufficiently high, not only would this tend to maintain a thicker liquid film and prevent the development of a metallic contact even for smooth surfaces, but the lag of the film in thinning itself as the projections on the journal and bearing tend to engage might save the film thickness from falling to the critical point of rupture. That is, if the time taken for the film over one of the bearing projections to thin itself to a value equal to the distance between it and the projection on the journal that may be passing over it is higher than the time required for the passage of the journal projection, it is evident that actual metallic contact may be avoided. Of course, this would involve an equivalent displacement of the axis of the journal shaft, but this would be simply superposed on its normal oscillations.

Now as we have seen, lubricants do not as a class successfully prevent the engagement of the surface irregularities of the journal and bearing under the conditions of thin film lubrication. Hence we must conclude that the film viscosities of practical lubricants are too low to prevent local contacts. On the other hand, the phenomenon of actual rupture itself does involve the separation of the molecules of the lubricant against their cohesive forces, and here there may well be significant differences between various lubricants. That is, while on the average the localized extreme pressures due to the projections of the bearing and journal coming into juxtaposition may create rupture with one lubricant only when the separation is of the order of five molecular diameters, in another case the critical thickness for rupture might be perhaps ten molecular diameters. Such differences will of course directly affect the coefficient of friction, even though the value of $\mu N/P$ determined for the system as a whole is the same for the different lubricants.

Another phase of the phenomenon of film rupture concerns the contraction of the film once it has been pierced by the projections from the metallic surfaces. This would involve the property of the adhesion of the lubricant to the metallic surfaces. While this property is also but little understood, it appears to be of a distinctly different nature than that of the molecular cohesion within the liquid body, as it involves the mutual interaction between the molecules of both the solid and lubricant.

After the projections which have pierced the film have passed over each other and the local extreme pressures have been relieved, the film will naturally tend to close and recreate the continuous liquid phase. Here will be involved the properties of the surface tension of the liquid and its wetting power with regard to the metallic surfaces. Thus if the surface tension is high and the film does not appreciably wet the metallic surfaces, the film will tend to break up into globules and droplets when pierced and ruptured by the many surface projections. Again, lubricants of the same viscosity might well show different behaviors in this respect since their surface tensions and wetting powers are not at all uniquely determined by their viscosities. Moreover, the temperature variation of these properties may be different for different lubricants, so that even if the surface tension and wetting power were of the same magnitude for two lubricants at room temperature, they would no longer be so at the temperature of the film.

As a whole, therefore, we see that in the region

of thin film lubrication the manifestation of new effects is to be anticipated. These will involve properties of the liquid which are of no significance in the motion of the liquid in bulk between rigid boundaries that are always separated by distances large compared to molecular separations. However, they are not fundamentally new physical properties of the liquid, but are such as are well known to be present when attention is focused upon the interfaces between liquids and solids or gases rather than upon the interior of the liquid itself. Indeed, it is because the true area of the surfaces to which the film of the lubricant is exposed under the condition of thin film lubrication becomes large as compared to its volume in the narrow portion of the wedge, that these surface effects begin to make themselves felt and therefore require special consideration. Here, we also find what is perhaps the main reason for the effectiveness of small additions of so-called oiliness agents in reducing the coefficients of friction under thin film lubrication conditions, although they would not be expected to affect appreciably the bulk properties of the liquid. For while in the bulk of the lubricant the concentration of the molecules of the oiliness agent may be only 1 in 100, the preferential adsorption of metallic surfaces for such molecules may result in a very high concentration over the actual surfaces in which, from the physical point of view, lies the seat of the phenomena of oiliness. Moreover the same forces involved in this preferential adsorption will give the adsorbed layer an effectively high film strength and diminish the tendency of the film to be ruptured or wiped away when the metallic projections on the journal and bearing pass over each other.

It therefore appears that although the so-called property of oiliness cannot be synthesized in detail from previously known characteristics of normal liquids, it is possible that it is merely a composite effect of the simultaneous action of the forces of adhesion, cohesion, and surface tension exerted in the film, and between it and the metallic surfaces when the film thicknesses become so small as to be of the same order of magnitude as the height of the natural projections on the journal and bearing surfaces.

Of course, it is to be emphasized that the physical picture presented here represents only a reasonable working hypothesis that might be used as a guide in further studies of these problems. Effects other than those we have mentioned, as the development of a mild corrosion of the metallic surfaces by the oiliness agents originally present in the lubricant or deliberately added, may very well play an important role in giving a polishing of the metallic surfaces during the running of the machine. Also the pressure coefficient of viscosity may require consideration when point contacts develop high instantaneous local pressures. Undoubtedly these effects demand detailed study in a complete investigation of the subject. But at the present we must content ourselves with the recognition of their existence, as a correct evaluation of their significance cannot be made without further research.

These few illustrations, selected almost at random from the numerous problems confronting a petroleum research laboratory, may serve to justify the title of the present address. The broad field of lubrication demands the attention of physicists, and basic work in the theory of the liquid state and surface phenomena should lead to results of immediate practical value. Many of you, however, will not be able to devote much attention to this interesting branch of physics in spite of the fact that it assumes such an important role in your daily lives. Perhaps after all it is unnecessary to worry over complicated details. Why not play safe and follow the precautionary example of the absentminded professor who changed his oil every day and his shirt every five hundred miles?

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*There was a time when, in the minds of many, science was but a plaything, and a plaything of the few, a time when it stood as a sort of fringe of disconnected mysteries bordering upon the black arts, a dangerous sort of thing capable of looking with equanimity upon the wickedness which lay on one side of it and with a hopeful and benign expression upon the conventionalities of life on the other. As its fruits became more and more evident, it gradually developed to a stage where it could be regarded, at least, as respectable; and, the main criticisms of it concerned its apparent uselessness. This was the age of adolescence of science.*

*Then came the period of maturity, when science, feeling the strength of its wings, could no longer harbor itself within the cloister, but came out into the open and made all the world its playground, and all the affairs of men its concern. The age of utilitarianism in science was upon us. More and more of the labor of men's lives was done by the product of man's intellect rather than through the sweat of his brow.*

*Science now stands ready, a willing servant, to reduce all the hardships of life to the ultimate minimum when we, her master, have learned how to direct her efforts and the skill which is within her.*

—From address of Dr. W. F. G. Swann on the occasion of the presentation on October 8, 1936, of the bust of Lord Kelvin to the Smithsonian Institution by the English-Speaking Union.

# *The Research Laboratory of the General Electric Company*

***A research laboratory is essentially a group of men, in a congenial atmosphere, engaged in extending the frontiers of knowledge.***
—W. D. COOLIDGE

## Historical Background

PROPER perspective for the appreciation of the work of a large research laboratory, such as that of the General Electric Company, requires a short excursion into the early history of applied electricity. The exact time at which the rather mysterious electrical demonstrations of academic lecturers began to be applied in everyday life is difficult to determine. Certainly however, sixty years ago, there were no electric lights, no electric locomotives or elevators, no large generators, no high powered transmission lines, and most important of all, no large commercial organizations interested in research. Yet, in three different sections of the country were men working alone who apparently had visions of the unlimited possibilities of electricity if only an efficient generator could be designed. These men were Charles H. Brush in Cleveland, Elihu Thomson in Philadelphia and Thomas A. Edison in Menlo Park, New Jersey. Because their pioneer work led eventually to the formation of the General Electric Company, short descriptions of their contributions are in order, although in many instances their work overlapped so much that it is almost impossible to give each his proper credit.

Brush (1849–1929) became interested in arc lights which had already been developed as laboratory curiosities but were not used commercially because of the high cost of batteries which was the only available source of power. He began in 1877 to develop a dynamo suitable for arc lighting. A few of them had been constructed by Europeans, but the continuous windings then in use on the armature resulted in a large internal resistance and consequently very poor regulation. Brush's design consisted of a multiple coil armature with short low resistance leads to the commutator which increased enormously the efficiency of the generator. Although designed for arc lighting Brush's dynamos found their first use in the electroplating industry and were first manufactured by the Telegraph Supply Company.

Continuing his work on arc lights Brush devised a regulator which enabled the operation of 2 lamps in series. The more lamps that could be operated in series, the higher was the efficiency because for a given power the current and likewise the internal losses in the generator and in the lines were smaller. A large exhibition of 12 lamps in series on the Public Square in Cleveland in 1879 drew crowds from great distances. It is said they were warned to bring smoked glasses to prevent damage to their eyes!

The first home of the laboratories (1900).

The success of Brush's arc lights led in 1880 to the formation of the Brush Electric Company and soon his system of lighting became widely known throughout the world. This company was one of the units which later merged with others into what was to become the General Electric Company.

A second unit was being developed at about the

same time by Elihu Thomson (1853–) who was a professor of chemistry in one of the Philadelphia high schools and was closely associated with the pioneer work in electricity encouraged by the Franklin Institute. In 1875, together with Professor Houston, he built a dynamo and two years later exhibited an improved system of arc lighting. The Thomson-Houston generator was a rather odd looking affair with a spherical armature. By the use of a magnetically controlled third brush the current could be kept constant no matter how many arc lights were connected in series. So successful was this generator that in 1882 the Thomson-Houston Electric Company was formed and a factory erected at Lynn, Massachusetts. Their system of arc lighting became the chief competitor of the Brush system. It is interesting to note that the general manager of this company was Charles A. Coffin who later became the guiding genius in the formation of the General Electric Company.

Contemporary with these advancements in arc lighting was the development of the incandescent lamp by Thomas A. Edison (1847–1931). In 1876 he stopped manufacturing his various telegraph inventions to organize a laboratory at Menlo Park for experimenting with lighting. Here, many years were spent in developing the carbon incandescent lamp which was exhibited in an early form in Paris in 1881. In 1882, he supervised the installation of the first central power station to provide incandescent lighting in New York. To take care of the increased demand for lighting brought about by the success of the central power stations, an Edison Lamp Factory was established at Harrison and an Edison Machine Works at Schenectady. In 1889 all companies with Edison's name were merged to form the Edison General Electric Company.

W. R. Whitney, vice president in charge of research.

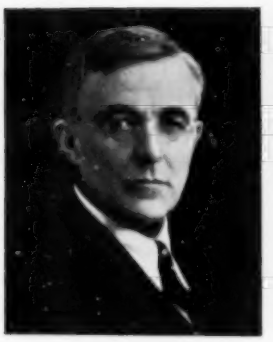
The great benefits that would accrue if all the resources and engineering and inventive talent in these three units were joined into one company was realized early by Coffin. First, the Brush Electric Company was acquired by the Thomson-Houston Company. Shortly thereafter, in 1892, the latter Company and the Edison G. E. Company merged to form the General Electric Company with Coffin as the first president. The technical director of the newly formed General Electric Company was Edwin W. Rice, Jr., who because of the traditions built up by the early pioneers decided to embark on a new experiment—*organized* industrial research. This project had the enthusiastic support of Professor Elihu Thomson, Dr. C. P. Steinmetz and A. G. Davis, manager of the patent department.

W. D. Coolidge, director of the laboratory.

Steinmetz came to the company in 1893, already famous for his accurate analysis of the hysteresis losses in alternating current machinery. Although he was primarily interested in applied research he deplored the lack of fundamental knowledge and wrote to Rice recommending the appropriation of a "considerable sum of money for the establishment of an electro-chemical experimental laboratory in our works, and further sums for its maintenance." He added "Absolutely essential for the success of this proposition appears to be that the experimental laboratory should be entirely separate from the factory and from regular production, so that no routine work interferes with experimental investigations." These suggestions were fully approved by Rice and, in 1900, Dr. Willis Rodney Whitney, a young instructor at the Massachusetts Institute of Technology was invited to come to Schenectady to organize a research laboratory.

### Early Days of the Laboratory

We have seen how all of the efforts of the early pioneer in the electrical industry were directed toward improving lighting. It is not strange therefore that Whitney was intensely interested



Irving Langmuir, associate director.

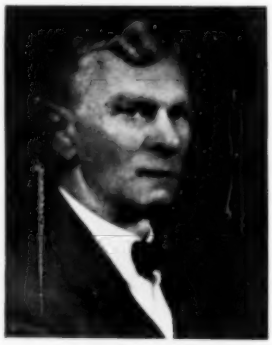
Saul Dushman, assistant director.

Albert W. Hull, assistant director.

in discovering the fundamental laws involved in the production of light by the electric lamp. Even before the laboratory was started the head of the patent department wrote to Rice, "You spend thousands of dollars and the best brains of the company in trying to add one-half of one percent to the efficiency of the generator . . . and yet this electric current, so carefully generated, transmitted and transformed, is sent into a lamp with an efficiency of something like five percent —or less." Here was a field in which there was plenty of room for improvement. Starting work in a barn, shared by Steinmetz, Whitney began his experiments. It happens that his first two problems, the application of magnetite as a motor-starter and the discovery of a means of properly coloring the mercury arc are still not completely solved to this day. The success of the research laboratory of General Electric Company is intimately connected with the fact that not a word was breathed about "immediate returns on the investment." Yet, after the laboratory got started, the returns were so great that any listing of them seems like gross exaggeration.

The first important useful success of the laboratory came from some experiments which Dr. Whitney was carrying on with the use of high temperature resistance furnaces. To test a theory of the cause of the blackening of incandescent-lamp bulbs, he put some carbon filaments inside his high temperature furnace. After removing them he discovered that the sign of their temperature coefficient of resistance was changed from the negative one of pure carbon to a positive one. Soon lamps with this new *General Electric metallized* filament were on the market under the trade name of Gem lamps. The company made great profits from these lamps but so also did the users because then they received twice as much light for a given cost as they did before.

Perhaps more important than the scientific work which Whitney did so well was his ability to pick valuable associates. In 1905, Dr. W. D. Coolidge was brought from M. I. T. In six years he was able to change tungsten from a fragile refractory material into a highly ductile substance that could be drawn into fine wires. In 1909, Dr. Irving Langmuir was brought from the Stevens Institute of Technology. He came principally to study a "vacuum." In a relatively short time he laid the foundations for the gas-filled incandescent lamp, the high power vacuum tube and atomic hydrogen welding, each of which has formed the basis of an entire industry. Later Whitney and his associates became interested also in the production of artificial fever by high frequency electro-magnetic radiation. They developed apparatus which in the hands of capable physicians is proving to be an invaluable weapon in combating some of the worst diseases.



L. A. Hawkins, executive engineer.

In 1928, Dr. Whitney was made vice president in charge of research and in 1932 he retired as director of the laboratory. In spite of this so-called "retirement" he is still busy at work every day in the laboratory on the biological applications of physics.

## Organization and Work of the Laboratory

At the present time Dr. Coolidge is director of the laboratory, Dr. Langmuir is associate director and Drs. Albert W. Hull and Saul Dushman are assistant directors. Mr. L. A. Hawkins, affectionately known as "Larry" by nearly the whole electrical industry, is the Executive Engineer who keeps the laboratory

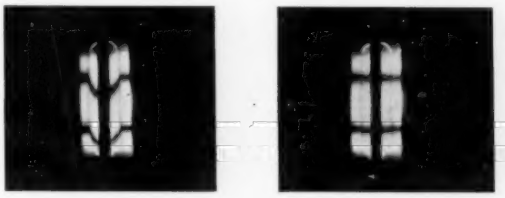
running smoothly and who brings to the attention of engineers the fundamental developments of the laboratory.

An important asset of the laboratory is the universal spirit of comradeship among all its staff. One senses it in Dr. Coolidge's definition "A research laboratory is essentially a group of men, in a congenial atmosphere, engaged in extending the frontiers of knowledge." Still further it is apparent in the pride that Dr. Whitney takes in the accomplishments of "his boys," in the manner in which Dr. Coolidge's eyes sparkle with enthusiasm as he describes the brilliant work of Dr. Langmuir, and in the understanding respect which each member of the staff has for his fellow worker. Without doubt the extraordinary success of the laboratory is due in no small measure to this spirit of comradeship.

The organization of the research staff of the laboratory has been made very flexible. Although there are a dozen or so different divisions under such headings as electronics, vacuum tubes, magnetic materials, x-ray tubes, etc., there are no hard and fast separations between the work which each section undertakes. Problems which arise within a particular division would of course naturally be carried out in that division although much help is usually given by the others. If a problem is brought in by one of the engineering laboratories, Dr. Coolidge, as director, assigns the problem to the division having the man who is most likely to obtain its solution.

Sodium vapor lamp and vacuum flask.

The division dealing with the physical and chemical problems associated with electronics is in charge of Dr. Langmuir. Several highly trained associates, including Drs. K. H. Kingdon, L. Tonks, J. B. Taylor, K. J. Sixtus and Katharine Blodgett, work with him. The properties of thin films are receiving much attention. Interest in this field may be well understood when one realizes that a monomolecular film of thorium on a tungsten surface causes the electron emission at a suitable temperature to be increased 100,000-fold, that the property of the decomposing of such gases as methane or ammonia by a hot tungsten filament is destroyed by a thin film of oxygen on the surface of the tungsten, and that in starting an arc a high electric field above a pool of mercury causes the rupture of its surface. Still further Dr. Langmuir has emphasized the importance of adsorbed films at the interface between oil and water because of their practical significance in the study of the cell walls of living cells. The delicate balance which is required between the concentrations of sodium, potassium, calcium, magnesium and hydrogen ions in the solutions containing living cells is duplicated in the physical experiments.



Strained and unstrained metal-to-glass seals viewed through crossed Nicols and quartz wedge.

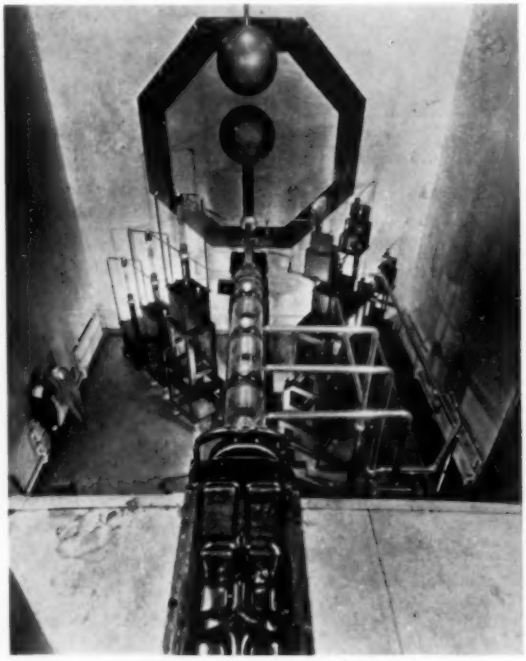
In Dr. Langmuir's division Drs. Sixtus and Tonks have conducted many experiments on the propagation of magnetic disturbances in iron and iron alloy wires. They make use of the fact that a wire of suitable material, for example, a ten percent nickel iron wire, when under a uniform strain has also a uniform direction of magnetization. By causing a large magnetic discontinuity at one point, the progress of magnetization along the wire can be studied.

The vacuum tube division headed by Dr. Hull is conducting three main lines of research. One of these in which Messrs. E. E. Burger and H. Poritsky are assisting is the development of alloys that can be sealed "vacuum tight" to glass. Two requirements in this work are that the glass "wet" the metal and that the stresses resulting from unequal expansion and contraction do not exceed the tensile strength of the glass. Dr. Hull and his co-workers developed an iron-nickel-cobalt alloy, which has been called fernico, which is especially suitable because its expansion coefficient changes at its Curie point in exactly the same way that the coefficient of one of the standard hard glasses changes near its annealing

point. This development has led to a new technique for glass-to-metal seals and has opened a new field of design for vacuum tubes.

Another field of activity under Dr. Hull's supervision is that of direct current transmission. This work is being carried on by Dr. C. H. Willis of Princeton University, and by B. D. Bedford and F. R. Elder of the research laboratory. They have devised a system of converting constant-potential a.c. power to constant current d.c. power which is transmitted and then reconverted to constant potential a.c. power. This system is characterized by unusual stability and reliability since, for example, the high voltage constant current d.c. line may be short-circuited without damage to the line or equipment. The changing of a.c. to d.c. and back again has been accomplished by means of specially developed thyratron tubes.

Still another type of research in this division is Dr. C. G. Suits' measurements of the temperature of the copper arc. This work has been stimulated by the increasing importance of electric arcs in such fields as arc welding, circuit interruption phenomena and arc illumination. The principal method used to determine the temperature involves the measurement of the time for a sound "wave" produced in the arc by a condensed spark discharge to go to a second spark discharge which is disturbed and acts like a microphone. This time is measured on a cathode-ray oscillograph and thus, the temperature may be calculated.



800,000 volt x-ray installation for medical service.

Many interesting experiments concerned with lamps and electrons are being carried on in Dr. Dushman's division. Here, with the assistance of Dr. G. F. Fonda and N. T. Gordon and C. G. Found and A. H. Young, the new sodium-vapor lamps have been developed. Laboratory lamps of this kind have an efficiency as great as four times that of an incandescent lamp of the same wattage. For many years, development was retarded because of the discoloration of the bulb caused by the diffusion of sodium atoms into the glass. A resistant borosilicate has now been produced which is used to glaze the inside of the bulb and thus the discoloration is practically eliminated. The life of these new lamps is as much as 4000 hours.

Still further progress in lighting is being carried out in Dr. Dushman's division. This is concerned with the recapture of the energy in the ultraviolet part of the spectrum produced by a mercury arc lamp and ordinarily lost for visual purposes. The secret behind this possibility is the use of fluorescence to transform the energy of short wave-length into that of longer wave-length, characteristic of visible light. This division is adding to its staff in the near future a "quantum-theoretical" physicist to investigate and if possible to learn the fundamental physics involved in the process of fluorescence.

A complete enumeration of all the research projects being carried out at this laboratory would be practically endless. There are, however, a few more which should be mentioned, at least. All previous voltage records for commercial x-ray tubes are now being broken by Dr. E. E. Charlton. The half-million volt cascade tube under construction is a marvel of glass and metal which has been made possible by the new alloy, fernico, mentioned above. This tube is, however, only a dwarf compared to the higher voltage tubes now under development. Other projects which can only be mentioned are, Dr. H. H. Race's method of measuring the endurance of insulation, E. L. Thearle's simple and rapid method of dynamically balancing armatures and

other rotating parts of machines, and K. D. McMahan's measurements and successful reduction of the noise produced by moving fan blades.

It still remains to say something of the size of the laboratory at the present time. It has a staff of 276 people classified as follows: technical staff 117, clerical assistants 23, shop force 122 and a miscellaneous group of 14. About 16 percent of the technical staff are physicists, 24 percent are chemists, 9 percent are metallurgists, and the rest engineers, draftsmen and laboratory assistants. It must be emphasized that this list includes only those in the laboratory at Schenectady known as the Research Laboratory. The General Electric Company has many other laboratories of various kinds which altogether employ several thousand people.

### The Laboratory Buildings and Equipment

The laboratory is housed in two buildings; one of seven stories and one of six stories providing approximately 140,000 square feet of floor space and almost 200 rooms. The research rooms are arranged so that there is available in each room city water, river water, illuminating gas, compressed air, vacuum, high and low pressure hydrogen, oxygen, live steam, low pressure steam and distilled water. A maximum of 250 kilowatts can be drawn from one or two terminal switchboards in each room; or connections can be made to any other room or to the basement distribution board, and from there to other laboratories in the plant. Work requiring 20,000 amperes, or 200,000 volts, or temperatures as high as 3000°C or as low as 200°C are also to be had with standard equipment.

The basement of one of the buildings is used to provide facilities which are in general demand, such as electric power, vacuum, liquid air, motors, transformers and rheostats. The first floor of this building contains the main offices, the library of 3000 volumes and technical journals, and experimental rooms for x-ray and cathode-ray investigations. Connected to the rear is a one-story section of 4000 square feet, used as a metal-working department. Its equipment includes rolling mills, 100-ton hydraulic presses, tungsten and molybdenum treating equipment, swaging machines, wire-drawing apparatus, high-temperature hydrogen furnaces, a ball mill, sifting apparatus and vacuum furnaces. A tile roof of this section provides space for outdoor experiments.

Present home of the laboratories.

As has been mentioned, the Research Laboratory is but one of several General Electric laboratories. In Schenectady there also are: (1) the General Engineering Laboratory, devoted to general and special engineering problems, including high voltage phenomena, the development and standardization of instruments and test methods, and the development of new apparatus like the photophone and the improved cathode-ray oscillograph; (2) the Testing Laboratory, for investigating the physical and chemical properties of materials, providing technical supervision for factory operations, devising new production methods and tools, and handling the day-to-day problems arising in manufacture, and (3) the Illuminating Engineering Laboratory.

At Lynn there is the Thomson Research Laboratory, where clear fused quartz and the supercharger for airplanes and automobiles, among other things, were developed; at Pittsfield there is the High Voltage Laboratory where artificial lightning of millions of volts is the toy of electrical engineers; and at Lynn, Bridgeport, Philadelphia, Erie, Fort Wayne and Pittsfield there are additional laboratories concerned with the production problems of those plants. There are the lamp development and illuminating engineering laboratories at Cleveland, specializing in incandescent lamps and illumination. And, finally, there are the many engineering sections of the different departments of the company, with much developmental and some research production to their credit.

# The Evolution of the Crystal Wave Filter*

By OLIVER E. BUCKLEY
*Executive Vice President*
*Bell Telephone Laboratories, New York, New York*

ONE of the most impressive features of organized industrial research is the evolutionary character it assumes when carried on over a long period of time. New inventions and discoveries breed others. An invention made ten years or more ago to fill a particular need at the time finds application today in situations that could not possibly have been foreseen when the original research was undertaken. Almost any important piece of telephone apparatus used in modern long-distance telephony would serve to illustrate this point. On examination one would find in it contributions from researches conducted for purposes very remote from the needs which the apparatus now meets.

The crystal wave filter, employed at the terminals of new broad-band telephone transmission systems, is a convenient and fairly typical piece of apparatus to examine and discuss in this regard. It is not spectacular in appearance, and, in this respect, is characteristic of many of the more important and less publicized products of the laboratory. In external appearance it is nothing more than a metal box measuring about $3\times5\times16$ inches, and designed to mount on central-office frames in accordance with our regular telephone practice. Within the box are a few apparently very simple pieces of apparatus almost as unimpressive as the box itself. No part of the assembly would attract particular attention from the casual observer, and yet it will reveal on careful study an interesting story of research.

A wave filter, of which the crystal filter under discussion is a special type, is a device that allows alternating current of certain frequencies to pass readily through it and that opposes a high impedance to currents at all other frequencies. Wave filters find many uses in modern telephony. In this instance the filter is part of a broad-band telephone transmission system; that is, a system which transmits a large number of conversations simultaneously over a single telephone line. The line may be a pair of open wires on poles, a pair of small wires inside a lead covered cable, or it may be a coaxial line consisting of a copper pipe which carries a centrally disposed insulated wire. This latter type of line is of special interest at the moment since a first practical trial of it is now being made. Fig. 2 shows the construction of the coaxial cable recently installed between New York and Philadelphia. This cable contains two coaxial lines, one to carry speech in each direction, and each capable of carrying several hundred independent speech channels.

The transmission of several conversations simultaneously over a single circuit, which in recent years has become quite commonplace, is itself a remarkable achievement of communication research. It is accomplished by transforming currents of the voice range, the region from about 250 to 3000 cycles, into currents of higher frequencies. A different frequency band is allotted to each of the conversations transmitted, just as different frequency bands are allotted to different programs in radio broadcast transmission. Not only does the same circuit serve to transmit a large number of conversations at different frequencies, but the same amplifier or repeater can serve for all speech channels with great resultant economy.

* Presented at the meeting of the Founder Societies of the American Institute of Physics, October 29–31, 1936 in New York.

With this type of transmission, known as "carrier transmission," the message carrying capacity of a circuit is determined by the width of the frequency band that the line and its associated apparatus are capable of transmitting effectively. If the available band width of the coaxial line is 1,000,000 cycles, for example, and if a frequency band 4000 cycles wide is allotted to each speech channel, 250 independent telephone conversations can be conducted over two of these coaxial pipes.

Crystal wave filters are used at each end of such a circuit—one for each speech channel transmitted in each direction. At the entering end, the filter serves to limit the transformed speech frequencies to those which fall within the assigned band, thus assuring that none gets into other bands to interfere with the speech in other channels. At the outgoing end, the filter serves to select a band of frequencies appropriate to it, and to guide the speech within that band to apparatus that returns it to its original form by relocating the frequency components in their normal positions.

To cover the entire range of frequencies that such a coaxial line can transmit would appear to require 250 filters at each terminal, each designed for a particular band of frequencies. In the interest of economy, however, only 12 different designs of terminal filters are used. These provide twelve 4000-cycle channels extending from 60,000 to 108,000 cycles, and each of these 48,000 cycle bands is then treated as a unit, and by a second step of modulation is relocated in its appropriate position on the frequency scale.

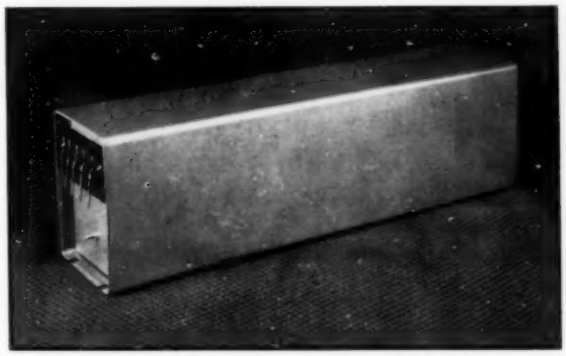


FIG. 1. In the crystal filter for broad-band telephony, an austerely simple exterior covers a most interesting combination of research products originating in diverse fields.

Filters play a very important part in the economy of broad-band telephone systems. This is partly because so many of them must be used—four for each two-way conversation—which puts a premium on low cost and physical compactness. But what is fully as important is frequency compactness, which determines the width of band that must be allotted to a speech channel. Because of the sharp cutoff of the crystal wave filter, it is practicable and economical to space the speech channels only 4,000 cycles apart.

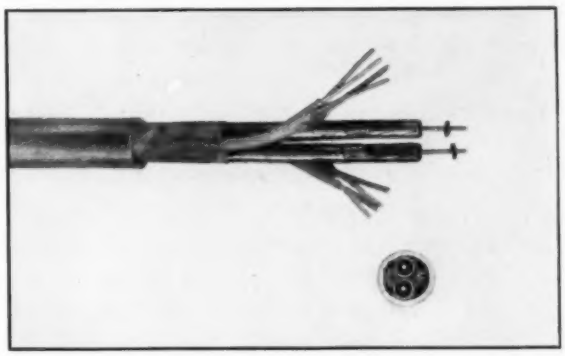


FIG. 2. A sample of the coaxial cable used on the experimental circuit between New York and Philadelphia.

If we removed the cover from one of these crystal filters, we should find a very simple assembly consisting of four quartz plates, four metal boxes containing inductance coils wound on a toroidal core of compressed powdered permalloy, two other metal boxes containing mica condensers, and eight tiny variable air condensers for the fine adjustments. Any of the essential parts of this filter would serve to illustrate the evolutionary character of development. Let us examine in this regard first the network itself, second the crystal, third the combination of the network with the crystal, and finally the coil. In each case we shall see evidence of contributions from many diverse directions.

To find the beginnings of the evolutionary train of thought which produced the network, we must go back more than thirty years to the time when Dr. G. A. Campbell, then of the American Telephone and Telegraph Company,

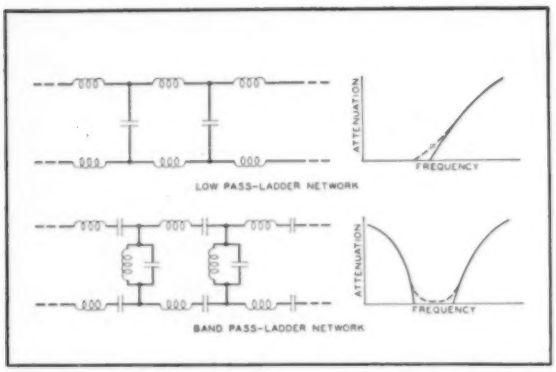



FIG. 3. Schematic of ladder type low-pass filter above, and of a band-pass filter, below. The respective attenuation characteristics are shown at the right.

was studying the possibilities of improving long-distance telephone transmission by loading, i.e., by inserting inductance coils in series with the line at regular intervals. Campbell did not stop with determining what inductance the coils should have and how they should be spaced, but went further and computed the characteristics of such a line for frequencies both within and beyond the range of those used in telephony. He discovered that the coil-loaded line, which transmitted telephone currents more efficiently because of inductance added by the coils, transmitted high frequency currents less efficiently because the inductance, instead of being distributed uniformly, was concentrated at the points where coils were inserted. The transition from improved transmission at low frequencies to impaired transmission at high frequencies was very striking. The loaded line was said to have a definite cutoff frequency, which was a function of inductance of the coils and their spacing along the line.

The loaded line is now looked upon as a low-pass filter, the loading coils providing series inductance and the line wires, shunt capacitance. Campbell was inspired by his discovery to study the general case of a reiterative ladder type network in which the reactances of rungs and side arms of the ladder were generalized. Two specific forms of the ladder type network are shown schematically in Fig. 3. One is a low-pass and the other a band-pass filter. Within the frequency limits of the pass band, the filter transmits currents without attenuation, but outside of the limits, currents are rapidly attenuated. Important variations of this network were later derived by K. S. Johnson, G. C. Reier, O. J. Zobel, and others, which made it possible to make combinations of filters to meet almost any practical requirements of band width and of terminating impedance, as well as to avoid reflections of waves at filter terminals.

Campbell later made another great advance in network theory when he derived the lattice type structure, shown in Fig. 4. This criss-cross network is a much more flexible tool than its predecessor of the ladder type. Sharper cutoffs at the edges of the band are obtained with it, and a greater range of characteristics becomes possible in practical filter design. One might expect that further complication of the network would lead to still further possibilities in these directions, but Campbell proved that the lattice structure was as effective as any symmetrical structure that could be derived from combinations of simple inductance and capacitance, thus greatly simplifying the task of later students.

It is unfortunate that it does not seem possible to explain the action of a filter simply in mechanical terms. A tuned circuit of inductance and capacitance is accurately analogous to a weight supported by a spring. One can devise a mechanical filter likewise from weights and springs in place of inductances and capacitances. One can even observe that it acts as a wave filter, but the explanation of its action is far too complicated to treat other than with mathematical equations, which we need not go into here.

When Campbell's wave filter was first developed no extensive practical need was apparent for it, but it was nevertheless quickly recognized as a tool of great potential value, and the need for it was not long in coming. The earliest commercial use of a wave filter in a telephone transmission system was made in the first transcontinental line in 1915 to prevent singing in telephone repeaters at frequencies above the voice range. A more extensive demand was created with the introduction of carrier telephone systems in 1916. From these beginnings the use of filters has expanded with great rapidity. Today we find the study of filters and related

networks among the most important and productive activities of our laboratories. Some twenty or more mathematically trained men now devote their entire time to network design, and a staff of five mathematicians are continuously engaged in research in this field.

Some indication of the importance of filters and related networks could be given by mentioning the large amount of money invested in them, but in another sense their actual value far exceeds any estimate in dollars and cents, for without filters many of the savings made in recent developments of long-distance telephony could not have been realized, and advances now impending would have been quite impossible. Indeed, the invention of the electric wave filter should be ranked as one of the most important in the history of telephony.

Until quite recently, nearly all of the filters developed for telephone transmission systems have been made from combinations of simple inductances and capacitances in ladder or lattice circuit structures, or in arrangements derived from those simple types. With all such filters the sharpness of cutoff at the edges of the pass band is dependent on the resistance associated with the filter elements. Condensers can readily be built with low resistance but practical inductances invariably embody at least the resistance of the copper wire of which they are wound, and if they employ magnetic cores, resistance is also contributed by hysteresis and eddy currents. It is true that the resistance could be made small by making the coils large, but this quickly runs into practical difficulties at telephone frequencies.

A possible escape from this limitation is to use in place of an inductance coil a mechanical element coupled to the electric circuit in such a way that its mass or inertia appears in the electrical circuit as inductance. Mechanical vibrating systems may be made with extremely small damping so that little mechanical resistance need accompany the inductance so secured. The stiffness of the spring supporting the mechanical mass will, of course, appear as capacity in the electrical circuit, and this must be taken into account.

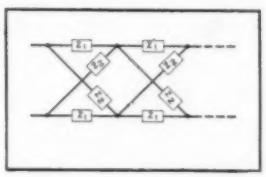


FIG. 4. Schematic of generalized lattice network.

The quartz crystal filter might be called a semi-mechanical filter. It is an electrical filter, but it uses mechanical mass to provide some of its inductance elements. The mass in this case is that of the crystal itself. This mass is transformed into inductance, and the stiffness of the crystal is transformed into capacitance, through the "piezoelectric" effect. Quartz is a crystal which generates an electromotive force when subjected to a mechanical stress; conversely, it changes shape when subject to electrical stress. Quartz has another property which is very important. It is a very stable material and can be obtained in large crystals of a high degree of purity. Indeed, we find by x-ray examination that the orderliness of the arrangement of its atoms is extreme.

Let us review some of the steps which led to the introduction of quartz into the filter circuit. The piezoelectric effect has been known since 1880 when it was discovered by the brothers Curie, but it was not until about 1917 that the effect began to receive serious consideration for practical uses. Indeed, there was no possibility of making much practical use of the effect until the vacuum tube amplifier became available. During the period of the World War, A. M. Nicholson of Bell Laboratories, made numerous experiments on devices employing Rochelle salt crystals, which display remarkably high piezo-activity. With them he made microphones and loudspeakers, and demonstrated a great variety of possible practical applications. About the same time Professor Langevin of France was making practical trials of quartz crystal oscillators driven by vacuum tubes to generate high frequency sound under water for use in the detection of submarines. Langevin's use of the crystal in this manner inspired others to experiment with it. Professor Cady in this country recognized the value of the quartz crystal vacuum tube oscillator as a source of radio frequencies of high precision. Following Cady's lead, experimenters in Bell Laboratories developed crystals accurately compensated for

temperature changes, and in this way produced frequency controls of very great precision. Today we find nearly all radiobroadcasting stations equipped with quartz crystal controls, and we also find them in small radiotransmitters such as those used in airplanes or in police patrol cars.

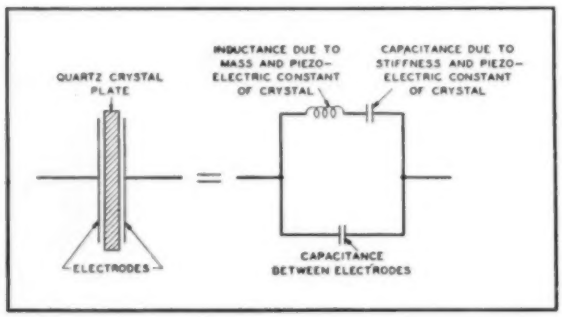

QUARTZ CRYSTAL PLATE
INDUCTANCE DUE TO MASS AND PIEZO-ELECTRIC CONSTANT OF CRYSTAL
CAPACITANCE DUE TO STIFFNESS AND PIEZO-ELECTRIC CONSTANT OF CRYSTAL
ELECTRODES
CAPACITANCE BETWEEN ELECTRODES

FIG. 5. Equivalent circuit of a quartz-crystal oscillator.

In its use as an oscillator, the quartz crystal with its attached electrodes behaves much as a simple electric circuit comprising an inductance and two capacitances connected as in Fig. 5. However, it is not possible practically to duplicate the performance of the crystal with actual coils and condensers. To build the equivalent circuit would demand coils having less than a hundredth of the resistance-to-reactance ratio of those which are available.

L. Espenschied, at that time of the American Telephone and Telegraph Company, first suggested that a ladder-type filter of sharp cutoff could be made by employing piezocrystals to supply equivalent inductance without the added resistance that is unavoidable when inductance is obtained by the use of coils. The band width that could be obtained with crystals in the ladder network, however, was too narrow to give it a very wide field of application. With this type of filter employing quartz crystals the ratio of the upper to lower cutoff frequencies had to be less than 1.008, which means that for a 60-kc carrier, the pass band could be only about 480 cycles.

W. P. Mason, of Bell Laboratories, studied the application of crystals to Campbell's lattice-type network in 1929, and found that by adding an inductance in series with each crystal element in the lattice, the ratio of the upper to lower cutoff frequencies could be increased to 1.135.[1] This made the crystal filter a practical device meeting the requirements of a band-pass filter for broad band carrier telephony. Crystal filters with and without the added inductances are shown with their characteristics in Fig. 6.

Further studies by Mason indicated that the inductances in the side and lattice arms could be wound on the same core and placed in the side arms as indicated in Fig. 7, which is a schematic of the actual filter used in the coaxial cable system. A bridging resistance was also inserted between the sections to help in sharpening the cutoff. In addition to these modifications the circuit finally evolved contains added capacitances in multiple with the crystal. These capacitances serve to control the width of the pass band and to permit fine adjustment.

In the lattice-type network as developed by Mason and embodied in the filter under discussion, the quartz crystals are cut in the shape of thin rectangles from 2.4 to 4.2 cm long, and with a width of about 50 percent, and a thickness of 2 or 3 percent, of the length. The two broad surfaces of the plate are coated with aluminum deposited from the vapor in a vacuum chamber. This process, now quite familiar to physicists,

[1] Space does not permit a full explanation of this and other steps in the design of the network. The reader is referred to Mason's original paper in Bell Sys. Tech. J. July (1934).

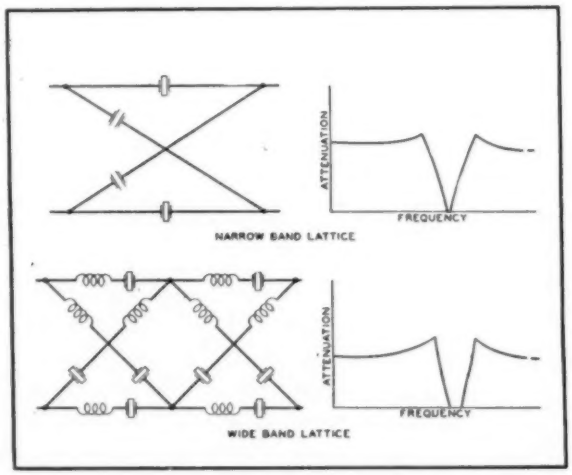



FIG. 6. With crystals alone, above, only a very narrow pass band can be obtained, but the addition of inductance, in series with the crystal, makes it possible to widen out the band over fifteen fold.

is the same as that employed in making astronomical mirrors. Electrical contact is made to the metal surfaces through the supporting points.

Such a crystal has several modes in which it may vibrate when excited with alternating voltage of appropriate frequency. There are five simple modes of vibration: two parallel to the edges of the plate, one perpendicular to the surface of the plate, one in flexure, and one in shear. The crystal may also vibrate in combinations and overtones of these modes, any of which may be excited with proper combination of exciting frequency and size and form of crystal. For this filter "longitudinal vibrations" are used, the length of the crystal determining the natural frequency of vibration. Crystals of four different frequencies are used for each filter, but the twelve different designs of filters employed for the groups of twelve 4000-cycle channels in each of the 48,000-cycle bands, are almost identical except for the dimensions of their crystals.

Although it is the length of the crystal plate which principally determines the natural frequency for longitudinal vibrations, the other dimensions are not merely a matter of convenience. Both width and thickness affect the natural frequency through internal elastic coupling among the several modes of vibration. They also, of course, affect the impedance of the crystal. Further, it is not enough to have a crystal which vibrates at the desired frequency. It is necessary too that it should not vibrate at unwanted frequencies. For if there should be a mode of vibration in the attenuating range near the cutoff frequency of the filter, the filter would pass frequencies which it is desired to exclude.

The first filters of this type were made with crystals cut with their thickness parallel to the *X* or electric axis of the crystal, their width being along the *Z* or optic axis, and the length along the *Y* or mechanical axis. It was found that crystals cut in this manner had a strong coupling to a shear mode of vibration, which would introduce an additional resonance at a frequency 40 percent higher than the desired frequency. This had the effect of introducing an added pass band at this point, which was undesirable. By studying the elastic constants and modes of vibration of quartz, Mason proved that by cutting the crystal so that its major axis made a small angle (about 18.5°) with the mechanical axis, as shown in Fig. 8, there would be no coupling between the longitudinal and shear modes of vibration, and accordingly the crystals for the filter were cut in this manner.

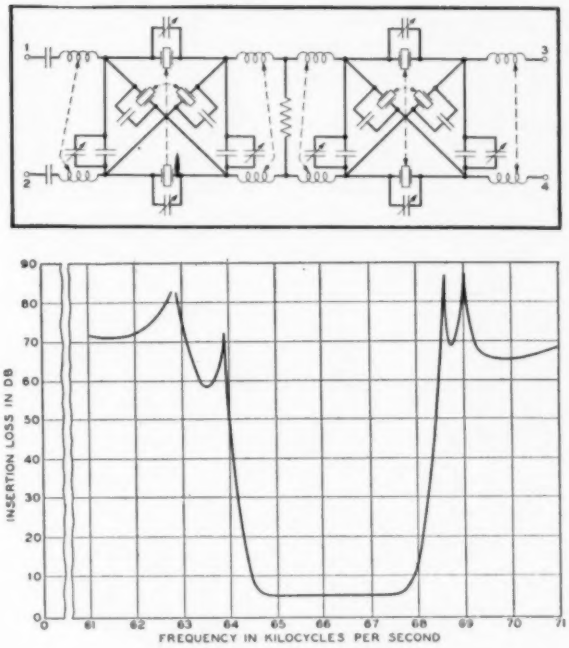



FIG. 7. Schematic diagram of a quartz-crystal band-pass filter above, and the filter characteristics, below.

In the circuit diagram of the filter, shown in Fig. 7, there are eight crystal elements whereas in the actual physical structure there are only four. This has been made possible by making one crystal serve for two. The aluminum plating is applied in two parts with a narrow unplated strip separating them. Electrically, therefore, there are two crystals, but mechanically there is only one.

The coils in this filter are also of special interest as a product of research. Their function is to provide inductance where more is required in the filter network than is provided by the equivalent inductance of the crystal itself. Since the filter is to be used at high frequencies, in this case up to 108,000 cycles, the coils must have very low alternating-current losses. Air-core coils can be made which will meet the electrical requirements, but the space occupied as well as the large magnetic fields is objectionable, and so cores of magnetic material are employed, but

it must be a material with extremely low hysteresis and eddy current loss. The requirement is met by a core of compressed powder of molybdenum permalloy. This material is itself one of remarkably high intrinsic permeability and low hysteresis, and by insulating the separate grains of the powder from which the core is pressed, eddy currents are kept very small.

These coils have another property which is quite important in this application. They maintain the same inductance over a very wide range of temperatures. This is unusual in coils with ferromagnetic cores, since permeability in general increases rather rapidly with rise of temperature. Molybdenum-permalloy is no exception in this regard, but its increase of permeability with temperature has in this case been compensated by incorporating with it a small proportion of an alloy whose permeability decreases rapidly with temperature. The resulting combination displays negligible change of permeability over the range of temperatures to which it is subjected in use.

The evolution of this core presents still another interesting illustration of physical research extending over a long period of time. In this case we must go back thirty years to the first application of inductive loading to telephone lines. The problem then, as now, was to obtain inductance with as little added resistance as possible. The best that could be done in the first loading coils was to use fine iron wire for the core. This wire had to be drawn to 0.004 inch diameter to hold the eddy-current loss to the required low value, and this feature made the coils very expensive.

The iron-wire core was soon succeeded by a core of compressed powdered electrolytic iron, the separate grains of which were insulated by a thin coating of shellac. This iron-powder core was used in loading coils from 1916 to 1927, when it was succeeded by the smaller permalloy-powder core, which in turn is now being succeeded by the still smaller and cheaper molybdenum-permalloy-powder core.

Permalloy is a nickel-iron alloy of very high permeability and low hysteresis, which was first developed for loading submarine telegraph cables. It is a tough, malleable metal, and considerable development work was required to

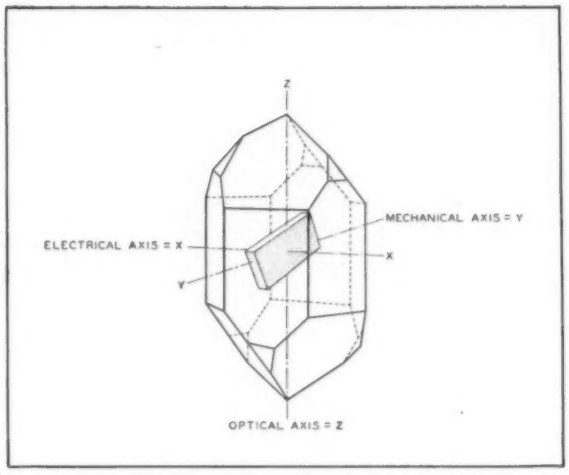



FIG. 8. The quartz plates are cut with their face perpendicular to the electrical axis of the crystal, and with ends and sides making a small angle with the mechanical and optical axes.

produce a satisfactory method of reducing it to powdered form. After the molybdenum permalloy has been powdered, the individual particles must be insulated. The insulation must be thin so as not to introduce too large a magnetic gap between adjacent grains, it must withstand the effect of compressing the grains into a solid mass of nearly the density of solid permalloy, it must be refractory so as not to be broken down in subsequent heat treatment, and it must retain its insulating quality through compression and heat treatment.

With the crystal wave filter, as with all other products of research, the task of producing the practical apparatus in form for manufacture and use was not completed with the solution of the problems to which I have referred. No less important are the many steps of engineering development that had to be taken to insure that the apparatus could be made economically and would always work. Among such steps were the development of methods of cutting and plating crystals, the development of a successful mounting for the crystal, provision for precise adjustment, shielding from electrical interference, and protection from moisture. In these features of the development we would find similar evidence of evolution.

Although it is impossible in a few pages to bring out the effort that has been expended in the past thirty years in developing this unimposing

but important exhibit, enough has been given, I trust, to explain what was meant by the statement that industrial research is an evolutionary process. A consequential feature of industrial research is that it is a long time in the doing and calls for patience not only from the investigator but from his financial supporters.

Another striking feature which is characteristic of nearly all research is that applications are found in quite unexpected fields. In this case researches on the loaded telephone line, the transatlantic cable, the use of crystal to detect submarines, the study of the diffusion of impurities through metals, the plating of metals by evaporation all found application in a way which could not possibly have been anticipated while the fundamental work was being done.

But the most important feature of all is one which the preceding discussion has done little to bring out. It has to do with the character of the men who brought this filter into being, and the spirit of investigation which guided them. Men of many types working in different fields of research have contributed their bit to this development, but these men all have certain characteristics in common, good minds as a foundation, many years of learning in the fundamentals of their science and the methods of research, and a cooperative attitude, for without cooperation of individuals these synthetic products of research could never be produced. Above all else, however, they had "the spirit to adventure, the wit to question, and the wisdom to accept and use"* which seems to me the best summary of the requirements for a research worker.

* From a lecture by H. D. Arnold at the Lowell Institute, Boston, Mass., Jan. 5, 1932.

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*The advance of modern physics today resembles in many ways the motion of an ameba. This small animal sends out pseudopodia in various directions. If one of these protuberances happens to extend toward some attractive morsel, the organism, through something analogous to a sense of smell, becomes excited. The other pseudopodia are withdrawn and the whole mass of the ameba flows into the pseudopod which received the encouragement. In the case of the ameba this process is very effective in taking the animal to its food.*

*The physicists of today behave in a similar way; they all tend to crowd into the extreme outpost, thereby withdrawing from other sectors. Of course, all analogies fall down if pushed too far. It may be objected that the advance in physics differs from that of an ameba in that it leaves a trail behind it. It is true, however, that the physicists do not seem to be aware of the need of adequately developing the side branches from their path of progress. Such work has too often been carried on by engineers without much further help from the physicist.*

—From an address by Irving Langmuir to The American Society of Mechanical Engineers, June 20, 1935

Dr. E. Q. Adams

# Physics in the Metal Industry*

Dr. Zay Jeffries

By

ZAY JEFFRIES AND E. Q. ADAMS

*General Electric Company*

*As time marches on metal research will utilize more and more the services of physicists.*

ON first thought it might seem that the metal industry is one in which the application of physics is a comparatively minor factor. If so, it is partly because whole sections of physics have been appropriated and have been given other names, such as, mechanical and electrical engineering, hydraulics, strength of materials, physical metallurgy, etc. In the broader view the metal industry is very rich in applied physics, both as primary and as secondary factors. Primary factors may be considered as those necessary for the accomplishment of a result, such as the physical separation of a liquid slag from a liquid metal by virtue of mutual insolubility and difference in specific gravity. Secondary factors are those used for convenience or refinement, such as, temperature measuring, recording and controlling devices, which may be incident to but not a part of the metallurgical operation itself.

Historically, it is more than a probability that the first metal industry was entirely one of applied physics. If, as many historians believe, gold was man's first industrial metal, it was recognized by its color, and its high specific gravity was used as a basis for its separation from the lighter weight rock material. While this operation, usually referred to as "panning," is prehistoric in origin, it is used prolifically even today, not only in prospecting for gold, but also for many other relatively heavy minerals containing, for example, tungsten, uranium, copper, lead, thorium, barium and a large number of sulfids.

Furthermore, the panning operation provides a most interesting study in physics. The operator must give Stokes' law, for the fall of a sphere through a viscous medium, an opportunity to function. Although this law was used by Wilson in calculating the number of water particles in a laboratory fog, and hence the charge and mass of the electron, it is, and has been for ages, the foundation of many ore concentration processes. In its simplest form the law states that under the action of gravity a sphere in a viscous medium fairly quickly acquires a constant velocity which is greater, in a given medium, the larger the sphere and the greater the difference in densities between sphere and medium. In the practice of concentration the pieces of rock are not spheres, so shape becomes a factor. Also the differences in specific gravity may be made more potent as a means of separating one mineral from another by feeding a concentrating machine with particles of nearly the same size, so prepared by screening.

But to return for a moment to the panning operation, it is a wonderful thing to behold what an expert panner can accomplish. Without the use of screens he makes separations quite the equal of those made by any machine. He incorporates many kinds and sequences of motions and uses different amounts of water at different stages. This operation is the forerunner of the concentrating machines in use today, such as classifiers, jigs, shaking and riffled concentrating tables.

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* Presented at the meeting of the Founder Societies of the American Institute of Physics, October 29–31, 1936, in New York.

Other physical methods are also used in the earliest stages of the metal industry, namely, in finding the ores. Again physics, *per se*, may be relegated to the background in this field because it is being appropriated under the name "Geophysical Prospecting." It is, none the less, applied physics.

Geophysical prospecting may conveniently be classified under four heads: magnetic, electrical, seismic, and gravitational.

The magnetic method is old and quite well known. A magnetic needle is used in such a way that deviations from the normal magnetic field of the earth are determined for both the horizontal and the vertical planes. The nearby presence of minerals permanently magnetic, such as $Fe_3O_4$ (magnetite) or those magnetizable in the earth field give rise to measurable deviations which are helpful in determining the location and extent of ore bodies.

Electrical methods are not only the most numerous, but are also the most complex and the most difficult to interpret. The electroscope is used to detect the presence of radioactive materials such as radium, thorium and uranium. Electric currents resulting from underground chemical changes are measured with sensitive galvanometers, the direction and magnitude of such currents providing some indication of the existence of minerals. Many kinds of electrical impulses, including direct current, alternating current with different frequencies, and radio waves, are applied in a systematic manner to portions of the earth's surface and variations from the values which should be obtained in a uniform medium are noted and plotted. While the interpretation of these results is far from perfect, it is improving with experience and the methods promise to gain in importance in the future.

Seismic methods are most effective in determining the depths of different layers of the earth's crust where adjacent layers show large differences in the velocity of sound, i.e., compressional wave, transmission. A charge of dynamite is set off at one place and seismographs are placed at a distance which is large in comparison with the depth of, say, dirt overlying a rock formation. The compression wave travels so much faster through the rock than through the air or overburden that the first impulse reaches the seismograph by a complex path, mostly through the rock. A series of such tests makes it possible to determine the depth of the rock with considerable accuracy.

Physics again comes to the front when the Eötvös torsion balance is used to detect nonuniformities in the gravitational field—more especially those caused by heavy materials.

Thus it is evident that physics has played, and is playing, a most important role in the discovery of ore bodies.

In the mining operations, too, we find the application of physics at every turn. The hardness and strength of the rocks, the flow of air through the pipes, mine lighting, impact phenomena resulting from high explosives, power supply, pumping and hoisting, represent only a few items involving much physics. One interesting application of physics in mining takes advantage of the knowledge of the physics of the air to effect so-called natural ventilation. Because cool air tends to flow downward, the differences in temperature between the air in the mine and that outside create natural drafts in openings at different levels.

In addition to the Stokes' law methods of ore concentration touched upon above, it seems fitting to mention another application of physics in this field which involves surface tension and adhesion phenomena. It is the flotation process, which has reached such prominence that many millions of tons of ore are treated by it annually. Certain minerals, mainly sulfides, have greater adhesion for a gas bubble or for oil than for water. Most gangue rock, like silica, shows more adhesion for water and still more, as a rule, for acidified water. A mixture of sulfide particles and gas bubbles and gangue particles in a solution, mostly water, may result in the bubbles attaching themselves tenaciously to the sulfides until the average specific gravity of the ensemble is less than that of the solution, whereupon the paradox occurs—the heavy mineral floats. Various reagents are used to provide the proper "froth" and to otherwise accommodate the idiosyncrasies of the different ores.

We cannot leave this subject without giving passing mention to the fact that ores are also concentrated by pneumatic, magnetic and electrostatic methods, all essentially physical.

Turning to the great smelting operations, chemistry and physics are at work simultaneously in many instances. The separation of slag from metal is physical, but chemical changes continue even up to, and often after, ingot pouring. These processes come, therefore, under the broad heading of physical chemistry. Many factors, such as gas flow, heat interchange, etc., are purely physical. In this field we shall content ourselves with two examples of treating smelter smoke.

The Cottrell process is used to separate solid particles from smelter smoke, either to make the smoke less objectionable or to recover the valuable flue dust, or both. Suspended particles may be ionized or electrically charged as a result of the smoke history or they may be charged by passing the smoke through an electric field. The charged particles are then precipitated on suitably arranged electrodes of a complex electrical circuit. Provision may be made, not only for the precipitation, but also for the removal of both positively and negatively charged particles.

The other example is the separation of flue dust from iron blast furnace gas. This is one of the most important applications of physics in the metal industry. Hundreds of millions of tons of gas are treated each year—in fact, an amount greater than that of any other manufactured product and greater than any commodity except water and coal. Around five tons of blast furnace gas are produced for each ton of pig iron. The world production of pig iron in 1929 was around 100,000,000 short tons.

The flue dust contained in the gas may be from eight to ten percent of the weight of the pig iron. It is recovered by a device which utilizes both Newton's first and second laws of motion, as well as Stokes' law. The "down-comer" pipes carry the gas from the top of the blast furnace to a so-called "dust-catcher." This is a much enlarged chamber which reduces the gas velocity, and hence its carrying power for dust particles. The gas outlet is in such location as to compel a marked change in the direction of flow. Most of the flue dust is projected to the bottom of the catcher, which is hopper-shaped and provided with a discharge means. Incidentally, the flue dust, after sintering, is recharged into the blast furnace, constituting a closed circuit.

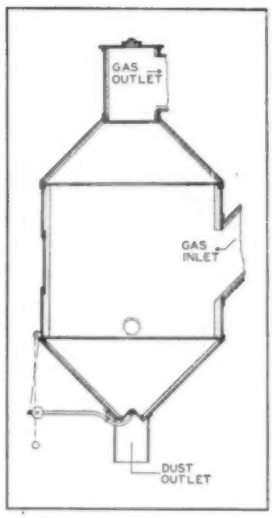


FIG. 1.

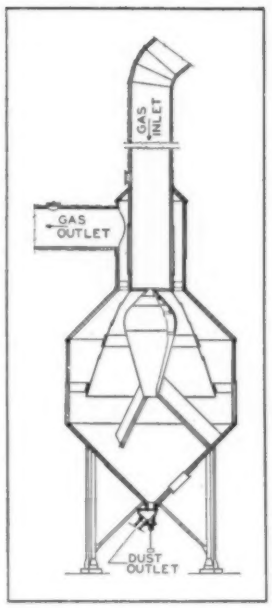


FIG. 2.

A new type of dust-catcher is of especial interest, not merely because it is much more effective than the older design, but because of the history of its development. Who would expect the Zeppelin art to influence iron blast furnace operation? Yet a noted blast furnace engineer attended a lecture on Zeppelins a few years ago and learned something new about the relation between eddy currents in air and streamlined shapes. He reversed the Zeppelin operation by putting a stationary streamlined shape in the dust-catcher. The gas hits this at about forty miles an hour, is reduced to about one-twelfth this velocity as a result of the enlargement of the chamber, and the eddy currents are so far reduced as to permit efficient separation of the dust. Thus the new physical principle of streamlining was added to those mentioned above.

Sometimes it is desirable to clean further part or all of the gas to make it less objectionable for use as a fuel for heating the brick checkerwork of the blast furnace stoves, or for steam boiler fuel, or to make possible its use for internal combustion engine fuel. In such cases another principle of physics is used, in the so-called "scrubbers" in which the minute solid particles are "wetted" and retained with the water.

Most of the operations in the metal fabrication industry are physical. Founding, for example, deals with surface wetting, viscosity, fluid heads,

crystallization, frictional flow and the like. As in some of the other fields mentioned above, these principles of physics have been appropriated by and have become an integral part of the founding art. So it is with metal-working where rolling, wiredrawing, extrusion and forging involve the application of the physical principles relating to pressure, tension, plastic deformation, impact, temperature, heat conductivity, radiation, coefficient of expansion and others. While welding usually involves chemical as well as physical changes, the latter are often dominating. Most of these operations are so commonplace that they need no further mention here, but this neglect does not detract from the tremendous importance of physics in the fabrication of all metal.

A few examples will be cited to illustrate some of the more unusual applications.

In the manufacture of electrical contacts by P. R. Mallory & Co., Inc. a tungsten disk is welded to a steel shank. A tray, holding many small steel shanks, is maintained in a horizontal plane, a thin disk of copper is placed on top of each steel shank, and a tungsten disk is placed on top of the copper. The ensemble is placed in a furnace with a hydrogen atmosphere until the copper melts, after which it is removed to a cooler zone so that the copper can solidify. In the earlier days great care was used by the operators to align the three parts so that the tungsten would be flush all around with the steel shank. It was later discovered that surface tension forces of the liquid copper properly aligned the tungsten disks no matter how badly off center. The tendency of the copper in a hydrogen atmosphere to wet both the tungsten and the steel, together with the nearly frictionless film of liquid copper on which the tungsten is free to move, permits the surface tension forces to dominate gravity and yield a minimum of liquid surface area. It is needless to say that this discovery made it possible for operators to fix the trays at a faster rate and with much less nervous strain. Any physicist would be delighted to watch one of these trays just as the copper is beginning to melt. He would see the tungsten disks darting into place, some moving one way and some another, but always centering themselves as if they had eyes.

Capillary laws are utilized in the manufacture of the welding electrode material known as Elkonite. Powdered tungsten is pressed into briquets and moderately heated, but not sufficiently to close the pores. It is then, in a hydrogen atmosphere, placed in molten copper—but not completely immersed. Capillary forces cause the copper to fill the pores even above the level of the liquid copper.

A beautiful application of coefficient of thermal expansion, modulus of elasticity and deflection, is found in the bimetallic strip used for temperature control. Two metals having different coefficients of expansion are rigidly joined together, as by welding, to form a composite sheet or strip. The strip bends one way when cooled and in the opposite direction when heated. The movement is reversible with change in temperature and the force tending to produce the bend is very great.

Another example where the different coefficients of expansion of two metals are used, not to produce motion as in the bimetallic strip, but to change the expansion coefficient, is the Dumet wire used to seal electric conductors in incandescent lamps and other sealed containers. A nickel-iron alloy wire of low expansion is encased in a copper sheath. The combination has about the same radial expansion as soft glass.

Among the secondary application of physics in the metal industry are those in connection with water supply, heat insulation, power, magnetic hoists or cranes, compressed air, lighting, lightning protection, and temperature measurement and control. We shall briefly discuss only the latter item. Here physical science has made a momentous contribution to the metal industry. Take temperature measurement and control away from the metallurgist today and he would be like a fish out of water. All the common devices utilize physical principles. The ordinary thermometer utilizes the difference in coefficient of expansion of the glass tube and the contained liquid. The resistance pyrometer uses variation of electric conductivity with temperature. In the thermocouple devices an electric potential is produced by the heating of a junction of two dissimilar metals. Optical pyrometers depend on the color matching of known and calibrated filaments with unknown temperatures, often by means of color filters. The radiation pyrometer

utilizes the radiation laws, including light emissivity factors, to reduce a very high temperature difficult to measure directly to a low one easily measurable. From the latter the true temperature of the body can be calculated. One of the more recent temperature measuring tools involves the photoelectric cell. Much is expected of the application of the photoelectric effect in future high temperature measurement and control.

The use of these devices has been the principal factor in putting the heat treatment of steel on a scientific basis. Many plant operations are also controlled by temperature measurement, and each year sees it policing additional operations.

### *Testing*

Judgment as to the suitability of metal parts for any particular service calls for both chemical and physical tests. Chemical analysis has been correlated with the potentialities of the material. With it one can at once reject the "sow's ears" from which it would be impossible ever to make a "silk purse," but *physical* tests are necessary to see whether full use has been made of the possibilities of the material.

The standard strength-of-material tests are physical tests. Strength in tension, compression, torsion or shear are physical properties of the material, and often as much dependent on the treatment of the metal as on its composition. Reduction-in-area is at first sight a merely geometrical property, but its dependence on the physical conditions of test makes it effectively physical.

These tests—like chemical analysis—have the drawback that they are destructive tests. The parts to which they have been applied cannot be used: consequently, one can have only statistical assurance of the quality of the undestroyed, and hence untested, specimens from the same lot. There is, consequently, need for nondestructive tests. These can probably never wholly displace the more searching destructive tests, but give an assurance of the quality of the particular piece tested that a sampling operation can never give.

The first and oldest of the nondestructive tests is visual examination. To the experienced eye, much is apparent as to the quality of a metal part: *some* incipient fractures can be seen at the surface, as may *some* cases of contamination by slag or dross, while the surface colors may give an indication of the heat or mechanical treatment. The hardness of the surface may be judged by scratch tests, or by the more refined indentation or rebound methods.

But a knowledge of the surface character is not enough. Hidden defects may be no less fatal to the safety of metal parts. The x-rays of Röntgen furnish the most direct method of internal examination. Without this method of testing, the recent developments in high pressure, high temperature steam engineering would have been greatly delayed, for the strength of a thick-walled tube is so little dependent on its external diameter that a material of dependably high strength is indispensable.

The safety of railway travel has been much increased by the ability to reject defective rails without waiting for service failure. For the initial examination of rails the x-ray has many advantages, but it has not yet been adapted for the examination of rails in service. For this, Sperry and others have developed electric and magnetic methods to find internal flaws which cannot be detected by external examination. The methods depend on the increase of electric resistance or magnetic reluctance caused by internal breaks in the continuity of the metal.

A magnetic test using colloidal magnetic material has recently been developed, and found to detect some defects not found by x-ray examination.

Tapping the wheels of railroad engines and cars to detect incipient fractures "by ear" is an old physical test. Supersonic vibrations offer another tool for the physical testing of metals whose possibilities we have not even begun to explore.

The phase changes involved in the quenching and tempering of steel are associated with changes in the magnetic properties which make magnetic tests useful indicators of the correctness of the heat treatment. For materials to be used for magnetic purposes, measurement of the permeability and hysteresis, or of remanence and coercive force, are as indispensable for electromagnets and permanent magnets, respectively, as measurements of electric resistance and its temperature coefficient are for parts

which are to carry a current. The desired resistivity may be low, as in electrical conductor material, or high for resistance or electrical heating elements.

In the case of tungsten wire for lamp filaments, the resistance after drawing tells little as to the filament resistance during the life of the lamp. Recrystallization at the high temperature of operation (a thousand degrees centigrade above the melting point of iron) brings a substantially constant resistivity. Nevertheless, erratically varying resistance of the wire after drawing is a useful indicator of the conditions of drawing.

The x-ray can give indications of crystal structure as well as of physical defects. With the x-ray the completeness of phase changes involved in heat treatment, grain size, crystal orientation, and certain impurities, may be detected in the metal part which one wishes to use, without any injury to it.

The spectroscope is used in many metallurgical laboratories both for quantitative and qualitative chemical analysis. It has no substitute in the determination of traces of impurities or small percentages of elements intentionally present in metals and alloys.

The metallurgical microscope is one of the prize testing devices. Metal surfaces are prepared by polishing and suitable etching to reveal the various constituents. The nature, amounts and distribution of the various constituents provide the metallurgist with information relating not only to the probable quality but even to the history of the preparation.

### *Research*

In one sense, research in the metal industry antedates written history, for the discovery and use of bronze and iron dominated the prehistoric epochs which have been named for these metals, and the steels of Damascus and Toledo earned a reputation which, even after discounting the legendary element, they have not yet wholly lost.

In another sense, the possibility of one branch of scientific metals research dates from the enunciation in 1874 by Josiah Willard Gibbs of the phase rule: a key which unlocked many of the secrets of the complex, and often confusing, alloy systems.

"In any system, *in equilibrium*, the number of degrees of freedom may be calculated by adding 2 to the number of components and subtracting the number of phases." The simplicity of this statement makes it difficult for those of us whose knowledge of alloy systems came after the somewhat tardy application of Gibbs' generalization to such systems, to put ourselves in the position of the pioneers whose study of the phases in ferrous and nonferrous alloys was made without this guiding principle.

A similar delay occurred in the application of the x-rays to the study of crystal structure. The possibility of using x-rays in *radiographic testing* was immediately apparent when Röntgen in 1895 announced the discovery of this penetrating sort of radiation; but it was not until 1913 when Laue and Bragg discovered reflections characteristic of the atomic and molecular arrangement in crystals—and solid metals are nearly completely crystalline—that the x-ray became an effective tool in the crystallography of metals. As an illustration, meteoric nickel-iron alloys show a banded structure, known as the Widmannstätten structure, but no such structure was found in artificial nickel-iron alloys or in meteoric material that had been treated above the phase-transition temperature. There was much speculation on the reason for this difference, but x-ray investigation showed the same phases present in both cases. The difference must then be that in the meteoric iron the cooling through the transition temperature has been so slow that a much greater crystal size was obtained.

A still more recent development is electron diffraction. Even now, this method seems to be the only one giving definite information on the crystalline nature of the polished surfaces of metals. The diffraction of electrons seems to be much more confined to the surface film than is that of x-rays. From these studies it now seems that highly polished surfaces are practically amorphous.

In the broad view, the marriage of physics and metallurgy has such a strong bond that the two cannot be separated. One cannot get far in physics without using metals as tools and subject material, and he cannot get far in the metal field without applying physics. It can never be predicted when the discovery of a new physical

property will lead to a new industry. Take electron emission as an example: for years it remained as an interesting physical phenomenon. The x-ray and radio industries now depend on it.

Are there latent industries awaiting the application of physical properties of metals now known only as laboratory curiosities? Very likely. Inasmuch as unpredictable applications of old and well-known physical properties of metals continue to come year after year, it is not surprising that the application of some of these lesser known and more recently discovered properties shows considerable lag. Often an advance in another art is the trigger which sets off such an application. Of what value, for example, to amplify a carrier wave if the message carried were not also amplified? The development of the carrier wave principle thus provided the impetus to utilize electron emission in radio and in the transmission of many telephone messages over a single circuit.

A mere thread of lead, if maintained at a temperature near absolute zero, could carry all the electrical energy available at Niagara Falls all the way to San Francisco without appreciable loss. This property of lead, tin, mercury, and some other metals, called supraconductivity, was discovered years ago by Kamerlingh-Onnes, but it has no practical application because it is so expensive to maintain such low temperatures. Work is being done now in two directions, first, to find metals which will show supraconductivity at higher temperatures and, secondly, to find more economical means to reach and maintain low temperatures. We are not suggesting that it is probable that the two researches will soon result in the practical application of supraconductivity, but we offer the thought merely as an example of the interdependence of developments.

Returning to the idea of the natural affinity between physics and metallurgy, we offer the opinion that metal research will utilize the services of physicists more and more as "Time marches on." The earlier investigations were along lines which were more or less obvious and required simple apparatus. The intense developments in metallurgy and physics have driven the metal researcher to the study of the subtle and involved relationships resulting from changes in the composition and treatment of metals and alloys, and to the use of the newest tools of physical science, no matter how complex. The trend in the recent past has been decidedly in this direction and it is becoming more pronounced. We believe this trend will continue, and hence our conclusion that the metal industry will in the future more generously apply physics and give employment, directly and indirectly, to more physicists.

The close bond between these two fields is further evidenced by the occasional appearance of a new alloy, like Invar, with no thermal expansion within an important temperature range, metallic resistance wires like Maganin with no, or even a slight negative, temperature coefficient of electric resistivity, etc., upsetting the orthodox physical conceptions and compelling a re-examination and augmentation of the fundamental knowledge relating to these various properties. Again, some new discovery in physics compels the metallurgist to examine known metals for new properties and often initiates a research for metallic substances exhibiting the new property in optimum degree. No matter in which field the new discovery arises, the net result is the enrichment of both art and science, and a forward step on the way to that goal toward which thinking man seems to be irresistibly impelled—a better understanding of nature's secrets.

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*In the advance of civilization, it is new knowledge which paves the way, and the pavement is eternal.* —W. R. WHITNEY

Edward Weston

# Edward Weston

## *A Pioneer In Instrument Manufacturing*

By ALLAN R. CULLIMORE

*President*

*Newark College of Engineering* *

THE death of Dr. Edward Weston on August 20, 1936, at the age of eighty-six marks the passing of a man whose contribution through research and invention in the field of applied physics can be appraised only with difficulty. His work culminated in the invention and commercial production of types of electrical measuring instruments ranging from those of the utmost precision and delicacy to those of the most practical and rugged construction. The mere cataloging of some 500 or so patents and discoveries which he made gives no idea of the spirit of the man or of his philosophy and indicates in no comprehensive way his vital contribution to research. This sketch then will concern itself very largely with some of the fundamental points of view and something of the spirit and the philosophy of the man who was one of the more important of our research workers in the field of applied electricity.

A man's work cannot of course be separated from his time, and Weston's life was an almost perfect example of the integration of an opportunity unique in the development of science and a man who by capacity, interest and training, was to do the thing which at the moment had best be done.

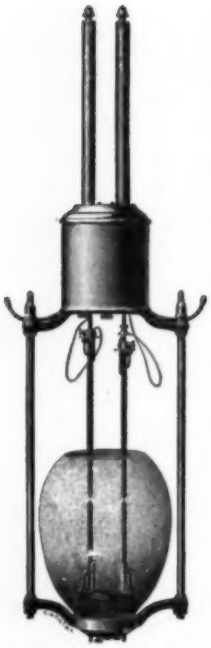
Weston was born at Brynn Castle in Shropshire, England, on May 9, 1850. At this time, science and particularly applied physics was at the threshold of a development hitherto without parallel in the scientific and industrial field. Much work had been done on the general nature of electrical phenomena, and there had been much fundamental research in pure science throughout the whole of Europe. In Germany, Helmholtz had expounded his principles of conservation of energy before the Berlin Physical Society in 1847. Ohm and Faraday were still making their fundamental contributions to the science of electricity. The spirit of Davy and Watt and their discoveries were still active and while the fundamental experiments of Galvani, Volta, and Coulomb antedated this era by almost half a century, their influence was still great.

Other fields of science as well were rapidly advancing. Charles Darwin was astounding the world with his theory of evolution. Louis Pasteur was in the midst of his bacteriological study and research. Gregor Johann Mendel was teaching physics in the Academy of Brunn and experimenting on the heredity of plants and animals.

At this time also, the recognition of the need for professional training and education in science manifested itself in the establishment in this country of schools of agriculture and the mechanic arts by the Morrill Act of 1862. In England, although industrial schools, mechanic institutes and other substitutes for apprenticeship had been established before the great World's Fair of 1851 held in London, the Fair showed England that technical progress and educational preparation for it was, on the continent, far ahead of her own. Germany had stolen the march by establishing her first technical school in 1745, just 106 years earlier, and was followed in 1795 by France with her Ecole Polytechnique.

Engineering as a profession was just beginning although the founding of the Rensselaer Poly-

* Dr. Edward Weston bequeathed to the Newark College of Engineering his scientific and general libraries, all his physical and chemical apparatus together with matters relating to his original discoveries, inventions and patents.



Double carbon arc lamp, manufactured by Weston about 1881.

technic Institute in 1824 had led to the development of civil engineering. Growing interest in technology and the application of science to industry during the period of Weston's childhood is evidenced by the establishment in America of such schools as Cooper Union (1859), the Massachusetts Institute of Technology (1861), the Worcester Polytechnic Institute (1865), Stevens Institute of Technology (1870) and the scientific schools of Yale and Harvard somewhat earlier.

By a peculiar coincidence then, Weston came into the world at almost the exact time when the work that he was to do was being recognized as a fundamental economic necessity.

After attending the primary schools of the church, Weston studied under tutors in Walverhampton, Staffordshire, where mining and metallurgy were, and still are, important industries. He became interested in both these fields and began to investigate electrolytic depositions of metal, as his first scientific study. Shortly thereafter he began to study chemistry and electricity.

By the time he was sixteen he was well acquainted with the known facts concerning the generation and action of electricity and had given a public lecture on the subjects. He also showed a remarkable capacity as a mechanic, dexterously making models for his experiments. This capacity, he inherited from his father who was a skilled mechanic far above the average.

Notwithstanding his interest in the study of pure science and its applications, and his mechanical skill, his parents urged him to study medicine and dentistry. He attempted to comply with their wishes, but finally refusing to continue study in that field, he left England. In 1870, when Edward Weston was twenty years old, he arrived in America.

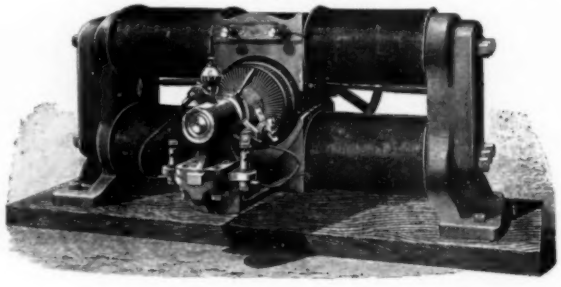
At this time, there were in America as well as in Europe inventors of ability and repute in many fields other than electricity. Matthew Baldwin had sometime earlier constructed railroad locomotives, while George H. Corliss had invented a steam engine. Goodyear's experiments which led to the vulcanization of rubber were carried on between 1830–1860. Cyrus McCormick had patented his reaper and many others were interested in the development of farm machinery.

Much experimentation was also being carried on along the line of electrical phenomena by a host of inventors, but Weston was keenly alive not only to industrial and commercial needs but also saw clearly the necessity for study, observation and experimentation in applied science, and understood and appreciated the principles of pure science.

If there was one thing which characterized his approach to science as a young man it was an overwhelming desire to learn the fundamental principles and theory and to find out what had been done before he started to experiment himself. One of the first steps in any of his investigations was to collect a library and procure all the material that he could possibly find touching his proposed line of endeavor. By successive steps, therefore, he built up one of the first research libraries in applied science. He realized perhaps more keenly than his predecessors or his contemporaries the relation between research in fundamental or pure science and research in technology. His work was characterized by a great appreciation of and dependence upon precise quantitative observation. From his very earliest experiments he realized the imperative fundamental need for precision instruments.

It would seem that the general technique or method of research in applied science, as we

Shunt wound generator, manufactured by Weston about 1882.



comprehend it today, was little understood. The lack of any real relationship between the observations of the early inventors and principles as even then laid down was marked. Mistakes were frequent and in many cases while the objective of the research was quite definite the actual experiments seemed to lead along many and diverse paths.

Two things seem to be lacking in the point of view of these investigators which Weston was to be able to supply. They were first the direction which the researchers in pure science gave to applied science, and second, the control which it was possible to exercise provided the theories were known and appreciated.

Weston seemed to appreciate better than any of his contemporaries the great value of theories and principles to substantiate and interpret the results previously obtained. He seems to have had the technique of modern research in mind when he consistently advanced from point to point only after the substantiation of his results in terms of the existing theories and principles. As a result of this particular attitude, he of course found himself adding to and modifying the fundamental theory in pure science as a by-product of his research in applied science.

Weston incandescent lamp, one of the first of its type. Made in 1884.

It is, of course, difficult to read into a man's life his entire philosophy, his spirit and the technique of his procedure, but such contact as the author has been able to make with the facts would lead him to believe that the basic qualities which characterized Weston's work were his sense of proper procedure, his ability to direct and to control, and to measure precisely. In this way Weston bridged the gap between the traditional type of inventor and modern man of research.

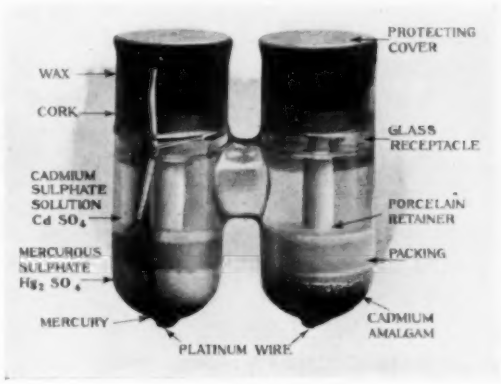
When Weston reached America he presented himself first to Professor Chandler of Columbia University, who it is related, treated him very kindly but was not able to offer him any immediate employment. Thereupon he interested himself first in the particular line of electrical work which was then nearest to commercial success, that is electroplating; particularly nickel-plating. In a few years his studies, designs and discoveries had improved the process, reduced time and costs and improved the quality of the finish obtained. He had also succeeded in allying himself with a firm which was commercially prominent in the field.

Dr. Edward Weston, at the time he formed his first company.

This alliance brings out an important characteristic of the inventive spirit in Weston; he was interested in immediately translating his discoveries and inventions into commercial products. Yet he went further than this. He was interested in the problems which had to do with manufacturing, management and distribution, and as a result, contrary to the experience of a vast majority of inventors of his time, he was able to transform his primary discoveries into commercial possibilities which were successful financially as well as scientifically.

In addition to this talent, his ability and skill as a mechanic enabled him to design and construct the machines with which to manufacture his inventions. This gift led to great speed in production, and when we appreciate that he

The Weston standard cell which was patented April 24, 1891.



was also intensely interested in the problems of management, personnel and labor as well, and with the problems of sales and distribution, we have a combination which perhaps it would be safe to say was almost unique, so far as the author is able to judge, in the annals of scientific discovery.

Because of the practical inefficiency of the primary batteries used for electroplating, Weston's attention was turned to the dynamo electric machine which had been partially commercialized by the work of Gramme and others. He realized that if such a source of electrical energy could be used and used efficiently it would solve many of the problems having to do with electroplating. He therefore undertook a study of the then existing dynamo with the idea primarily of making it a practical and efficient transformer of mechanical energy.

The original Weston instrument factory in the early 80's. Here the first Weston instrument was produced.

His study was undertaken and carried out with the same philosophy and spirit which characterized his earlier studies. The work was as precise and quantitative as it could be under existing conditions. In this study as in all his work he was hampered by the fundamental lack of precision instruments and by definite standards of measurement.

His success with the dynamo was exceptional and in a very few years he had succeeded in building machines with an extraordinary high efficiency for that time. Before long, he was associated with a company which was manufacturing these machines and again these machines were successfully put on the market and distributed in a time which even today would have been considered very exceptional.

In his studies of the dynamo, Weston's attention was naturally attracted to the great possibilities of this machine as a source of power particularly for lighting, and he made extensive studies of systems of electrical distribution which led him into a rather wide field of electrical research.

Particularly was he interested in the carbon in use in arc lamps and the filaments in incandescent lamps, and his studies in both fields were not only fruitful from a scientific point of view but were again almost immediately reflected in commercial production and distribution.

In considering all these lines of endeavor we are struck by the versatility of the man and by the efficiency and the speed which characterized the transformation of the discovery to the finished commercial product.

During this particular period Dr. Weston devoted himself to many other lines of work and made certain outstanding researches in the field of electricity, all of which pointed the way toward what might be termed his culminating achievement—the establishing of the standard of electromotive force in the Weston cell and the manufacture of precision instruments.

Perhaps we can get a better perspective of the contribution of Edward Weston as projected against the inadequacies of his time when we realize that when he first started to work in the field of electricity commercial production and distribution of electricity was nonexistent, that electroplating was in its infancy, that electric lights were not commercially useable, and that electric motors were not commercially developed. More important still, there was no absolute standard of electromotive force and no instruments capable of measuring precisely electrical quantities. Dr. Weston, as a pioneer in science, supplied these.

# Educating Physicists for Industry*

By SAUL DUSHMAN

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THE topic which you have invited me to discuss this evening is one which, as we all realize, is of extreme importance at the present time. The American Institute of Physics in this country and the similar organization in England are vitally interested in increasing the number of possible openings for physicists in industry and other fields. Everywhere there is a feeling that the curriculum of education for physicists, as carried out hitherto in academic institutions, is not adequate to meet the needs of our age. Whereas there is hardly any difficulty in obtaining work in industry for graduates in the departments of chemistry and metallurgy, graduates in physics find that very few industries require their services and that their training is quite inadequate to meet the requirements of the openings that might be available. What are the fundamental causes for such a condition of affairs? How can the situation be improved?

It is evident that in the consideration of the subject there are three interested parties. Firstly, there is the industry or other human activity in which physicists might presumably be of service to the community. Secondly, there is the student who, in entering upon a training in physics, assumes that the college will give him such an education as will enable him to earn a living through the exercise of his accumulated knowledge and experience. Finally, there is the college which is in the position of a manufacturer, as it were, putting forth a certain brand of product and seeking both to create and to supply a demand for its graduates.

Each of these three parties may be regarded as a separate aspect of our topic. Industry makes certain demands of the trained physicist. What type of student can best meet these demands? How can the college give an adequate training to the right type of student?

### *I. The Physicist in Relation to Human Activities*

Let us consider the first of these aspects. What is the nature of the service which industry may justly demand of a trained physicist? The work of the physicist, like that of the chemist in industry, falls into one of three classes:

(1) Fundamental research,
(2) Development problems,
(3) Process control work.

The significance of fundamental research is too well known to require much comment. It is identical in methods and motives with the type of investigations along purely scientific lines that is carried on in our best academic institutions as post-graduate studies. Such work is necessarily of a long-range type. No immediate results are expected. The initial motive in starting the investigation is one of curiosity, a desire to understand better a phenomenon or

* This address was delivered before the Pennsylvania Conference of College Physics Teachers at State College, Pennsylvania, on October 16, 1936. Attention is also directed to the papers by Dean Homer L. Dodge and by Dr. A. R. Olpin in the Symposium on the Training of Physicists for Industry at the meeting of the Founder Societies of the American Institute of Physics in New York, October 29, 1936. These papers will be published in the December 1936 and February 1937 issues of *The American Physics Teacher*.—EDITOR

group of observations. Of course, in industry, there is always the latent hope that the knowledge thus gained will prove useful in an economic sense, but the existence of such an objective is not permitted to influence the mode of attack of the problem, nor is there any undue pressure to attain results of a utilitarian nature.

While investigations of this type may lead to results and conclusions which are of greatest interest scientifically, they may have to be carried on over a period of many years without any visible return to the stockholders. Indeed, it may be difficult often to justify such work on any purely material basis, and to permit the prosecution by its employees of research activities along purely fundamental lines requires both a breadth of vision on the part of the executives and extensive financial resources. Therefore, only government institutions and the more affluent industrial organizations can actually afford the financial investment involved. Furthermore, only a relatively limited number of men trained in science have the requisite attributes for success in purely fundamental research lines.

Consequently, by far the larger percentage of graduates in science must be trained for developmental and control work. For it is in these fields that most of the trained chemists have found employment, and it is in the same type of work that the majority of physicists must expect to engage. At a conference on the training of industrial physicists which was held by the British Institute of Physics, in February of this year,[1] a similar conclusion was expressed regarding the opportunities for physicists.

It is extremely difficult often to differentiate between the type of investigation of which the motive is the desire for increased knowledge and that in which the objective is that of developing some new device or process. In such cases fundamental research merges by imperceptible gradations into the type of research work which is directed towards a specific purpose.

On the other hand, it is also just as difficult to draw a clear distinction between the work of the physicist and that of the engineer. In fact, it is quite a common experience that both these types of trained men may cooperate in the development of a certain device, or in the solution of a specific factory problem. And since engineering is, as a matter of fact, applied physics, the question might well arise as to whether the trained physicist should not limit himself to purely scientific work, while leaving the application aspects to the engineer.

This is a question which, undoubtedly, could be debated at great length. However, I believe that the physicist can make extremely valuable contributions even in these fields which are assumed to be the prerogative of the engineer. What is the distinction between an engineer and a physicist? I have tried for many years to find an answer to this question and to the accompanying one, which is the following. Why does one student go into electrical engineering while his companion at high school goes in for physics? I can give only the results of my personal observation, and the conclusion may be quite erroneous. Nevertheless, it would appear that there actually exists a difference in the mental temperaments of the two students, with the result that one goes in for pure physics while the other takes up applied physics. This difference can be described briefly thus: Given the same set of observations, the physicist asks himself, "What is the explanation?" while the engineer asks himself, "How can I use these facts?" The engineer is, in general, a specialist in a certain field of applied physics, and his training does not give him that wide knowledge and breadth of view which is characteristic of the physicist. As a consequence, the engineer is rarely interested in the fundamental or basic principles.

I trust that there is no misunderstanding of the above remarks. No invidious comparison is intended. It is merely a statement of what I believe to be a difference in human attributes. In the following section I shall discuss this topic in greater detail, and the only point to be emphasized in the present connection is that there are opportunities in industry for both the physicist as well as the engineer. But, and this is extremely important, if the physicist is going to work with the engineer in industry, he must also learn to speak the language of the engineer, to understand his point of view, and in short, to cooperate with him in every respect. For it is the engineer who is responsible in most organizations for getting a particular job done. Over a century

[1] J. A. Crowther, J. Sci. Inst. **13**, 141 (1936).

ago an English engineer, Tredgold, gave the following definition of engineering: "The art of directing the great sources of power in nature for the use and convenience of man." If the physicist in industry will bear in mind the specific functions of the engineer and cooperate with him intelligently in the furtherance of their common objectives, he will create not only essential goodwill for himself but also more opportunities for other physicists.

In other papers submitted at this meeting and also in the forthcoming symposium in New York, a number of illustrations will be given of the types of developmental and control problems with which a physicist in industry is apt to be confronted. It is therefore not necessary to discuss such illustrations in the present paper. However, in this connection it would seem fitting to stress the fact that other opportunities are also available to physicists in related branches of science.

During the past few years there has developed a new field for the application of physical methods to the determination of mineral and oil locations. Geophysics is beginning to absorb graduates in physics and, as shown by the work of Dr. P. D. Foote and his associates, this application of physics has not only proven profitable commercially but also extremely interesting scientifically.

Biophysics is another field in which few physicists, as far as I am aware, have become interested. For a number of years Professor H. B. Williams of Columbia University has been pioneering in a branch of applied physics in which there are countless opportunities. Medical therapy uses a number of devices developed by physicists, such as high voltage x-ray tubes, sources of ultraviolet, high frequency oscillators and radioactive elements. No doubt artificially radioactive elements will also be used in the near future. The electro-cardiograph is typical of a number of electronic devices that have proven invaluable in diagnosis. The older methods of diagnosis which depended upon hunches and guesses are being displaced by scientific methods based on quantitative measuring devices which the physicist has developed. In all the large hospitals one or more physicists should be just as essential as the medical man.

But biophysics also offers the physicist as well as the chemist an infinitude of problems in the study of biological processes. Closely allied are the problems of plant growth and soils. The work in this field of the Boyce-Thomson research laboratory is too well known to need further comment, and there is urgent need for more investigations of the same kind, carried out in a dozen laboratories all over the country.

Lastly, there is still another branch of science in which the physicist should exhibit more interest than he has in the past. Metallurgy is, as yet, largely an empirical science, in which the practice is far ahead of interpretation and theory. We have a vast body of information on methods of testing metals and alloys for specific uses and on methods of treatment for attaining desired properties. We have a great deal of data on their properties both thermal and electrical, but only such data as are useful to the metallurgist and engineer. We have no comprehensive point of view to interpret these observations, and outside of a few investigators in Germany and England, very few physicists in this country have considered the possibilities, both scientific and industrial, of a cooperation between physics and metallurgy in scientific investigation and development.

At the present time possible openings in these allied fields for research and development workers trained in physics have been considered by relatively few teachers in physics. Students are not usually aware that such fields even exist. The further investigation of opportunities in these lines is one of the many tasks which, I am sure, the American Institute of Physics will undertake in cooperation with the universities and local physics clubs, for we must educate not only the physicists but also the public to the various kinds of activities into which physics actually enters and may contribute if given an opportunity.

### *II. Necessary Attributes of a Physicist in Industry*

Now let us consider the attributes which a physicist must possess in order that he shall be accepted as a member of an industrial organization. The requirements in this respect are the

same for all employees, whether they be physicists, chemists, engineers, or salesmen.

In a number of industrial organizations it is quite customary for each individual in a certain group to be rated periodically by his associates. Naturally, these records are quite confidential, and in order to eliminate the possibility that the person who does the rating is prejudiced against the man whom he is asked to rate, three or four other members of a group are asked to rate the same individual. Now it is of interest to note that while adequate technical knowledge is the first qualification, there are a number of other qualifications in respect to which the individual is rated, and these are mostly of the type which are innate in the individual, such as integrity, reliability, industriousness, originality, initiative and ability to cooperate with other men. Furthermore, and this is of greatest significance, a consideration of the relative values assigned to the different qualifications in typical rating sheets shows that the nontechnical attributes count for at least 80 percent of the total rating.

Some years ago Dr. C. R. Mann, of the Carnegie Foundation, sent to a number of engineers the question: "What are the essential qualities of a successful engineer?" The relative importance of the different qualifications is attested by the following average estimates, based on 1500 replies:

| | | |
|---|---|---|
| 41 | percent | character |
| 17.5 | " | judgment |
| 14.5 | " | efficiency |
| 14 | " | understanding human nature |
| 13 | " | technical knowledge.[2] |

Thus, technical knowledge is actually only one of many factors which govern the suitability in industry of technically trained men. These other factors, it will be recognized, are those which concern first the character of the individual and second his relation to other individuals in the same group. Mental integrity is the most essential quality. Then follow industriousness, originality and initiative. In a modern organization team-work is an absolute necessity. No single individual no matter how brilliant, can accomplish any results worthwhile, and in judging new men I would sooner take the opinion of a mechanic or glass-blower than that of another technically trained man, because it is in his actions and behavior towards those not blessed with similar education that the real character of a man is exhibited.

In this connection mention should be made of a necessary qualification which has been discussed extensively during recent years. It is commonly designated by the word "personality." I have consulted a number of my colleagues regarding their interpretation of this word, and while there is wide diversity of opinion, there is general agreement in regarding personality as the integrated attributes of an individual which makes for the utmost confidence and respect of his associates. While there has been a tendency to overestimate the importance of this qualification, it is nevertheless to be recognized as a highly desirable attribute when accompanied by a high standard of scholarship. I have been impressed frequently, as no doubt everyone else has, with the fact that some individuals create a prejudice at first glance, while others invite further acquaintanceship.

One of the most interesting studies in which men can engage is that of man himself. All of us have such varied characteristics, attributes, and abilities. Great talents in certain directions are latent in each of us. Sometimes these hidden abilities are discovered and developed into their full possibilities; at other times they remain latent and ultimately disappear. Success, as I see it, consists not in the accumulation of material wealth, but in the fullest utilization of those innate abilities with which nature has endowed us.

Can a college education do anything to bring out such attributes as character, judgment, reliability and so forth? Obviously all that can be accomplished is the development of these qualities when latent in the individual. All men are not equal in intelligence, ability and character. Johnson O'Connor in his most interesting book *Born that Way*[3] has given most convincing evidence based on a large number of tests for the validity of this conclusion. The qualifications that are required for a purely scientific investigator are different from those demanded of one

[2] Quoted by A. W. Hull, "Qualifications of a Research Physicist," Science **73**, 623 (1931).

[3] The Williams and Wilkins Company, Baltimore, 1928.

who is to carry on development or control work. The student who thinks as a physicist could rarely succeed as an organic chemist or biologist, while the pure mathematician rarely has an understanding of the thinking processes of a metallurgist. The physicist interested in theoretical investigations seldom makes a good experimenter. Consequently, it should be the function of the college to attempt to guide each student into that activity for which he seems to be best adapted. How that might be accomplished is, I am aware, a problem of considerable magnitude; but such a policy would prevent a potentially excellent chemist from striving to become an astronomer. It would eliminate some of the disillusionment and disappointment that so often comes to graduates when they realize through the failure to obtain a job that their time in college has been wasted.

### *III. The Education of a Physicist for Service to the Community*

So far we have considered, first, the nature of the services which a physicist can render in industry and in connection with other organizations, and second, the type of individual that is desirable in organized activities. What kind of training shall be given to students, so that they shall be able to meet the requirements of the various possible openings?

First of all let me deal briefly with the education of the physicist for purely scientific work. As mentioned previously the incentives for such work and the method of investigation are the same whether carried out in the material environment of industry or in the intellectual atmosphere of a university. It is becoming more and more customary to employ for this type of research the same type of man as would make a successful investigator in academic life. A Ph.D. degree is considered essential, as evidence that the possessor has an aptitude for research activity. Consequently, the type of education need not be essentially different from that required for a higher degree by any of the recognized institutions.

Now let us consider at greater length the nature of the training for those physicists who should be fitted for developmental and control activities. In some institutions there have been developed to meet this requirement courses in engineering physics. Probably you will label the course which I shall outline tentatively as a training in engineering physics. The designation is, however, immaterial, if in such a curriculum you *retain the fundamental attitude of the physicist* and do not permit the engineering department to manage it according to their views. As I have already emphasized there is a basic difference between the philosophy of life held by those whom we designate physicists and that held by engineers. Let us make the physicist more practical, more versatile, more broadly educated; but let us preserve that critical, searching attitude towards nature which distinguishes pure science from engineering.

Obviously, since physics and mathematics provide the backbone of such an education, these subjects should be the most important. The course in physics should emphasize fundamental principles and concepts, rather than compendious details which are quickly forgotten after examination. There is, as far as I am aware, a woeful lack in most of our textbooks of practical illustrations. The applications of mechanics, heat, sound, light, electricity, and magnetism are all about us in everyday use, but little or no attempt is made, except in rare cases, in the teaching of these subjects, to connect the statements in the textbook with the applications. Physics can be made a subject of human interest, but instead it is made an exercise in logic and mathematical technique. Not that I object to either. Physics is an exact branch of knowledge in which observation, reasoning, and deduction are closely interwoven. But let us not confuse the shadow with the substance.

By contrast let me note that students in chemistry are made to realize from the very beginning the intimate connection between their branch of science and industry. For instance a discussion of the chemical properties and preparation of $H_2SO_4$ will be accompanied by a picture and description of a modern plant. Does any textbook on physics contain an adequate description of the mechanism of an automobile, or of a modern electrical generating station? Here is physics put to work, and yet the student is virtually told that such matters are of interest

only to mechanical or electrical engineers. A great deal could be accomplished in this respect by well-written stories about applications of physics in industry. I understand that this is one of the projects which the American Institute of Physics will foster in the immediate future, and undoubtedly it will be of great assistance in bridging the gap which now exists in the teaching of physics, between theory and practice.

Mathematics is usually taught by pure mathematicians who are interested in refinement of logic and in their subject as an end in itself. But for the physicist mathematics is a tool, and a very useful one at that. Hence, the mathematics ought to emphasize the practical aspects. Let the students be taught the use of graphical methods, and let them be taught a broader but less intensive training in a number of mathematical fields. When the need arises, the capable student can fill in gaps in his knowledge by going to the proper sources. The main thing is that he should know the type of problem which can be treated by a given mathematical technique, and he need not waste his time learning all the by-paths and pitfalls which delight the mathematician. Would I advocate therefore that mathematics be taught by a mathematical physicist? By no means. Let the mathematicians teach the fundamental courses as far as differential equations and Fourier's series, teaching them along broad lines, and let a physicist show the students how these mathematical methods fit into the solution of problems which are of practical interest.

Fortunately there are now available a number of textbooks in which there are excellent illustrations of the function of mathematical analysis in the interpretation of physical phenomena. There is a great deal that is instructive and stimulating in the study of the fundamental generalizations which have been derived by men who were "likest gods." There will always be a small percentage of students who will enjoy this intimacy with the great mathematical intellects of the past and present. But for the large percentage of students, who are so-called practically-minded, the teaching of mathematical physics is made altogether too large a part of the course.

There seems to be a general impression that classical physics is being sacrificed in our present curriculum to courses in advanced theoretical physics, such as those dealing with quantum mechanics and nuclear physics. The emphasis is placed on the theory rather than on practice, so that while the graduate may be quite familiar with the theory of dispersion, he does not know how to set up and adjust a spectroscope or diffraction grating. Or he may be very familiar with the Fermi-Dirac theory, but not be able to connect up a set of vacuum tubes and a thyratron to transformers and capacitors, for use in some practical experiment.

It is of interest in this connection to quote some comments from an address by Dr. F. B. Jewett.[4]

> "Graduates in electrical and mechanical engineering," he writes, "are generally more adaptable than physicists to the problems of industrial research and development relating to physics. They more readily adapt themselves to the handling of apparatus and equipment and are usually more successful in the use of their hands. They have in general a better physical insight and a greater appreciation of practical requirements for carrying through a developmental program.
>
> "It probably does not make a great deal of difference what specialized type of training is received by a certain few men with a natural inclination to industrial problems.
>
> "We do feel, however, that too little stress has of late been placed upon the fundamental physics by most American universities, especially in graduate work. The universities are producing physicists who apparently are well qualified to publish worth while researches in spectroscopy and atomic structure, but who have had almost no training in basic mechanics, hydrodynamics, electrical theory and thermodynamics, such as was taught thirty years ago. We believe that in an industrial laboratory, the physicist or engineer who has the fundamental classical background is of greater value than a physicist who has almost exclusively specialized in the modern physical developments."

To remedy this defect, the student should be given extensive laboratory work, not on experiments that are already set up, but under conditions where he has to assemble the necessary equipment, and obtain results. During the fourth year or even before, each student should be given some relatively simple problem. We are always in search of information on the properties of materials. A glance through such compendia

[4] "Modern Business Looks at Secondary Education," School and Society **31**, 415 (1930), quoted by A. W. Hull, reference 2.

as the *International Critical Tables* or *Tables Annuelles* shows that there are immense gaps in our information on many substances that are of scientific and technical importance. For the theoretical physicist the lack of such information may mean the difference between a plausible theory and a working hypothesis. As is well known, some academic institutions have developed excellent technique in certain types of measurement. A student who has spent a semester in such work will gain a better appreciation of both accurate experimental technique and of the field in which his results are of interest.

Next to physics and mathematics, comes chemistry. It is a subject which the average student of physics prefers to neglect, and he usually regards his course in this subject as an unavoidable evil. No doubt some of you have heard the witticism that a chemist is an individual who knows a little physics and wishes he knew more, while a physicist is a gentleman who knows no chemistry and thanks kind fates for this ignorance. The physicist is unconsciously snobbish with respect to chemistry. He is the inheritor of traditions which originated with the mathematical physicists of the 18th century. They were the supermen who intended to solve the problems of the universe by one grand differential equation. On the other hand, since the chemists are the spiritual descendants of the alchemists and similar persons of ill repute, it was but natural for the physicist to close his nostrils and incidentally, his mind, when in contact with chemists.

While Ostwald first brought physics into chemistry and Willard Gibbs could visualize the essential similarity of chemical and physical reactions, the physicist has never learnt the really useful kind of thermodynamics such as is taught in any good course in physical chemistry. As a result, the physicist is singularly unaware of the differences between free and total energy or of the many useful results that have been deduced by the applications of these concepts to reactions of various kinds.

Physical chemistry is a subject that ought to be compulsory for all physicists. The fundamental knowledge, thus obtained, of thermodynamics, colloid chemistry and electro-chemistry will prove an invaluable asset. This ought to be accompanied by a course in inorganic chemistry and a briefer course in organic chemistry.

For in industry and everywhere else outside of college problems do not arise in general as applications of pure physics or chemistry. Physics and chemistry, as taught in college, deal with idealized observations. For pedagogical reasons we divide physics into various topics and chemistry into an equally large number of topics and segregate one group from the other, usually in different buildings. But nature is one and indivisible. In the language of physics we can describe natural phenomena in general as involving an interaction between a number of different factors, some chemical, some physical. According as one set or the other predominates we label the phenomena physical or chemical. But in practice it does not pay to forget any factors which may be of importance, whatever their label.

It is hardly necessary to give illustrations, but I shall mention two. What could be more purely chemical than the manufacture of glass? Yet a physicist like Schott revolutionizes this industry and a concern like the Corning Glass Company finds it essential to use physicists along with the chemists. Turning to the electrical industry we find that in the behavior and properties of dielectrics there are just as many chemical as physical problems. The physicist in industry may find it quite necessary to consider the chemical factors which govern the behavior of a glass or resin, and under such circumstances it may prove useful to know that $SiO_2$ is an acid and ZnO a basic radical, that resins are polymers of rather complex molecules which are derived from phenol, or some other organic molecule. In short, it might prove a distinct help in the investigations upon the behavior of such substances to have the "feeling" of a chemist for possible explanations of some of the observations.

It has always been a cause of bewilderment to me that a chemist can learn some physics, at least enough to know how to use it, while a physicist can rarely learn even the simple rules of valency. Everywhere in industry materials are being used, and a knowledge of the chemistry of these materials is of just as much importance

as the facts concerning their physical properties. It has been stated innumerable times that a physicist makes precise measurements with impure materials, while a chemist makes inexact measurements on pure materials. An adequate training would eliminate such a state of affairs.

The physicist in industry must possess adaptability and must be versatile. As is well known most industrial operations involve the use of electrical power and of electrical apparatus. Without at least an elementary training in d.c. and a.c. electrical engineering the physicist in industry cannot get very far. The lecture-room course in this subject should be supplemented by tests in the electrical engineering laboratory, so that the student may learn the difference between a transformer and a generator and how to close a circuit-breaker without setting the building on fire or killing himself.

There are an ever increasing number of applications of electronic devices, both of the vacuum and gas-filled type. The knowledge of the operation of these tubes obtained in the physics department should be extended by instruction from the electrical engineering department in circuits and applications.

The question has been debated as to whether a physicist intending to go into industrial work should not also have a course in drawing. I should prefer to leave this question open. However, there is no doubt that a knowledge of scientific German and French is absolutely essential. The industrial physicist as well as the academic physicist should keep in touch with most recent developments in his particular field, and the inability to read some of the publications as they appear in scientific journals may be a serious handicap.

Lastly, but not least, the graduate should be able to speak and write correctly in his own language. This point has been emphasized repeatedly but will nevertheless bear repeated stress. Ability to communicate ideas to others whether by word of mouth or pen is one of the prime requisites in human organizations. It is an art which may be learnt with practice and patience. I would have the student write essays, but not upon so-called literary topics. Why should not the topics be chosen from the student's scientific studies? He would thus gain experience not only in expressing himself clearly and accurately but also in arranging ideas in a logical sequence. It would also serve to impress upon him the significance of many concepts in science. The wise teacher could even use his students to assist him in searching for the most recent papers in the literature on a given topic, and in the arrangement and preparation of the material for a lecture. In this manner the student will also obtain experience in consulting the literature.

Some of you will probably consider the program which I have outlined quite strenuous. No doubt it is, but then life is a great deal more complex now than it used to be twenty-five years ago; competition is keener, and standards are higher because of this very fact. That institution will attract the best type of student which succeeds best in fitting its graduates for life.

It would seem highly advisable to lengthen the curriculum to five or even six years. The period in excess of the regular four years could be utilized for training in research and special lines. For instance, if the student is interested in metallo-physics or biophysics the graduate period could be utilized for acquiring a better foundation in either metallurgy or biology. It is probable that in the future opportunities in industry and other lines will be available only for those men who have had a post-graduate training in research. This need not be of the same type as that now customary for a Ph.D. What is desirable here, again, is a broader type of experience than that which a student normally obtains by spending a couple of years on a special problem that is often of purely academic interest. While a Ph.D. is practically essential for employment in purely scientific investigations, the physicist engaged in developmental and control work has much greater need of a more varied experience.

Finally, there is one idea which I believe the college would do well to impress upon its graduates. It is that expressed by the late Dr. Charles Eliot when he stated that a college education should give men "*the trained capacity for mental labor, rapid, and sustained.*" Such capacity, once acquired, is an attribute which should not be neglected even after graduation.

In science, more than in almost any other branch of intellectual activity, education really begins when the graduate enters upon his life-work. While business men and similar individuals may spend their leisure in other ways, the scientist must continue to burn the midnight oil throughout his whole life. He must advance along with the younger generations, because to cease from advancing, to let down on his studying and investigating means intellectual stagnation and ultimate failure in his professional activity.

### *IV. Concluding Remarks*

As I stated at the beginning, some of my audience, perhaps quite a number, will disagree with certain of my opinions. I realize only too well that the curriculum which I have outlined may appear to you impractical in many respects and for various reasons. But I trust that these reasons will not be largely the result of what has been designated as "wishful thinking." There is a conservatism in all of us that opposes change, but if we deal in a thoroughly scientific manner with the problems which we have discussed, it is certain that the results achieved will be worth while.

In concluding, there is just one other thought for which I would ask your serious consideration. You who are the teachers of physics have also inherited the traditions which would make the study of physical phenomena an end in itself. This tradition has developed an attitude which resembles much more that of the philosopher than that of the engineer. If you are going to train physicists to take a more active part in the work of the world about you, then the first task is that of modifying your own point of view. There must be a sympathetic understanding on your part of the requirements of industry and of your duties towards the men who come to you in the hope that they will be fitted to meet the requirements of industry. The very fact that you have arranged for a symposium of discussion on this topic is an indication that you have this desire to assist the oncoming generations to be of greater service to the community. I am sure that the American Institute of Physics will do its utmost in helping you to carry out these ideals and that with your active cooperation, success will crown your efforts.

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*Once again, there has been a hue and cry to find new industries to provide employment. Critics have called our technologists barren and impotent because they have not passed another modern miracle and given birth to some great new industrial activity. But we know what the limitations are, and the long period of pure scientific research, invention and technical development which must first lay the foundations. Herbert Hoover, while Secretary of Commerce, gave a warning that was generally unheeded because generally not understood when he pointed out that industrial development was so rapidly overtaking pure scientific discovery that industry ran danger of a shortage of new "building blocks" on which to build. Well, no group has been more eager to find new industrial projects than has the national government during the period of the depression. But though urged, by one technical group after another and even from within the governmental group itself, to follow the one proven and sure path to this objective by stimulating research in the basic sciences, no constructive action has yet been taken.*

—Karl T. Compton, Address at Public Utilities Forum of Investment Bankers Association

# Contributed Original Research

## The Magnetostrictive Oscillation of Quartz Plates

R. C. Colwell and L. R. Hill
*West Virginia University, Morgantown, West Virginia*

Small quartz plates were vibrated by mechanical impact from magnetostrictive rods cut to the proper lengths. Sand scattered on the plates gathered at the nodal lines and produced figures similar to those on Chladni plates. The quartz plates were then vibrated in an electrical field produced by the same vacuum tube circuit which was used to vibrate the magnetostrictive rods. Electrical and mechanical vibrations gave exactly similar patterns on each crystal provided the frequencies were identical.

SYMMETRICAL figures similar to those on Chladni plates have been produced on small quartz plates by Wright and Stuart.[1] The plates were vibrated at high frequencies in an electric field. The patterns show how a plate breaks up into segments giving overtones as well as the fundamental frequency. It is also possible to excite quartz plates mechanically by means of magnetostrictive rods. Sand scattered upon the surface of the crystals will gather at the nodes and the resulting patterns reveal the nature of the vibrations. All the crystals used were Curie cut, that is the electrical axis of each crystal was perpendicular to the major face with the optical and mechanical axes in the plane of the major face.

The magnetostrictive rods were first cut to approximately the right length by the use of the formula

$$\text{Length in centimeters} = 258/\text{Frequency in kilocycles.} \quad (1)$$

They were then machined to the exact frequency needed for any particular crystal by a method of trial and error. Considerable difficulty was encountered in the production of the mechanical patterns due to lack of stable power transmission between the rod and the crystal. This difficulty was overcome by machining the end of the rod until it was absolutely plane. The end was then etched with a mixture of glacial and acetic acids. This treatment produced a surface which gave good contact between the rod and crystal so that the rod could set the crystal into violent vibration.

The rods were excited by a power oscillator using a type 852 tube with a graphite anode. The circuit (Fig. 1) was extremely stable at the frequencies used. The wire in the coils $L_1$, $L_2$ must be sufficiently heavy to prevent any great change in temperature while in operation. The power supply must be very steady and free from any sixty-cycle ripple. The oscillator must be extremely stable in operation since the slightest deviation in frequency will prevent the pattern from forming. The inductance $L_1$ was a 600 turn coil of No. 22 wire with a tap one third of the way up from the grid end. The form on which it was wound had dimensions $2.5 \times 2$ cm. The magnetostrictive rods passed through a hole in the center of this form. The inductance $L_2$ had five or more sections with 400 turns per section. The voltage in these sections was very high so that heavy insulation was required. The crystal holder is shown at $B$. It was made of brass plates of the same size as the crystals. Each crystal rested upon a small glass plate shown in the figure so that none of the crystal surface touched the brass. The upper brass plate was 0.5 cm above the crystal. The rest of the circuit was of conventional design and will be understood from the figure. The part of the circuit enclosed in dotted lines was used to put a very high electrostatic field upon the crystal; it was not needed for the magnetostrictive rods. The sand figures were produced electrostatically in the holder $B$; but they could also be formed in the electrostatic field of the coil $L_1$.

The magnetostrictive figures were produced as follows: the bar was clamped at its center in a precision clamp and

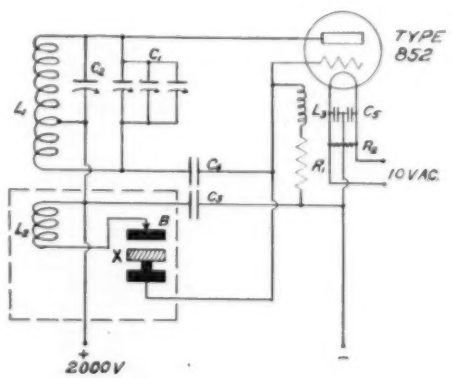


FIG. 1. $C_1$—0.0005 mmf var. condenser 2000 v
$C_2$—0.00025 mmf var. condenser 2000 v
$C_3$—0.001 mmf, 5000 volt mica condenser
$C_4$—0.01 mmf, grid blocking condenser
$C_5$—0.01 mmf, by pass condenser
$R_1$—10,000 ohm, 40 watt resistor
$R_2$—100 ohm filament resistor
$L_1$—plate inductance; $L_2$—high voltage inductance
$B$—holder for quartz crystals.

[1] R. B. Wright and D. M. Stuart, Nat. Bur. Stand. J. Research **7**, 519 (1931).

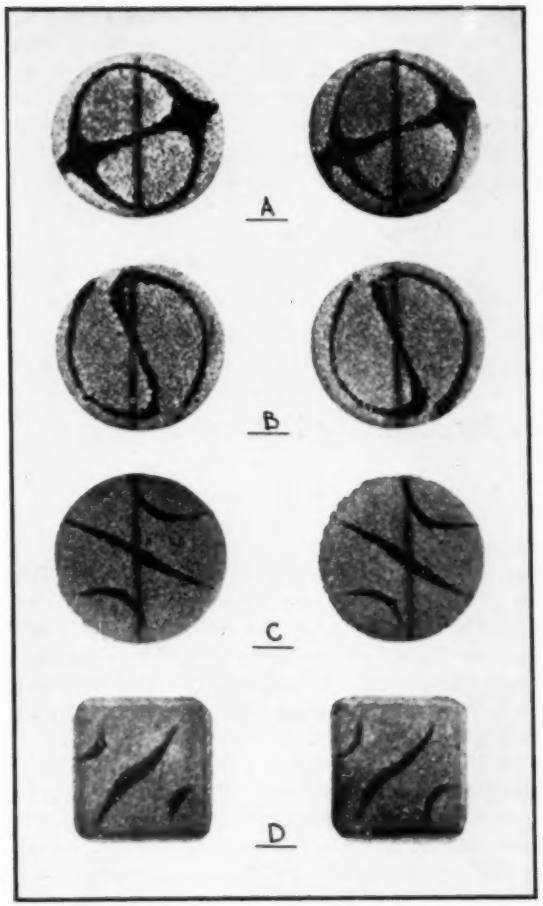


FIG. 2. (*a*) (*b*) and (*c*) are the dimensions of the crystals. The electrostatic patterns are on the left, the mechanical on the right.

| | | |
|---|---|---|
| *A*—(*a*) 0.491 cm<br>(*b*) 3.50 cm | bar—length 3.51 cm<br>diam. 0.782 cm | freq. 73.1 kc |
| *B*—(*a*) 0.491 cm<br>(*b*) 3.50 cm | bar—length 3.27 cm<br>diam. 0.75 cm | freq. 78.4 kc |
| *C*—(*a*) 0.491 cm<br>(*b*) 3.50 cm | bar—length 4.95 cm<br>diam. 0.792 cm | freq. 51.7 kc |
| *D*—(*a*) 0.478 cm<br>(*b*) 3.00 cm<br>(*c*) 3.06 cm | bar—length 4.62 cm<br>diam. 0.752 cm | freq. 54.7 kc |

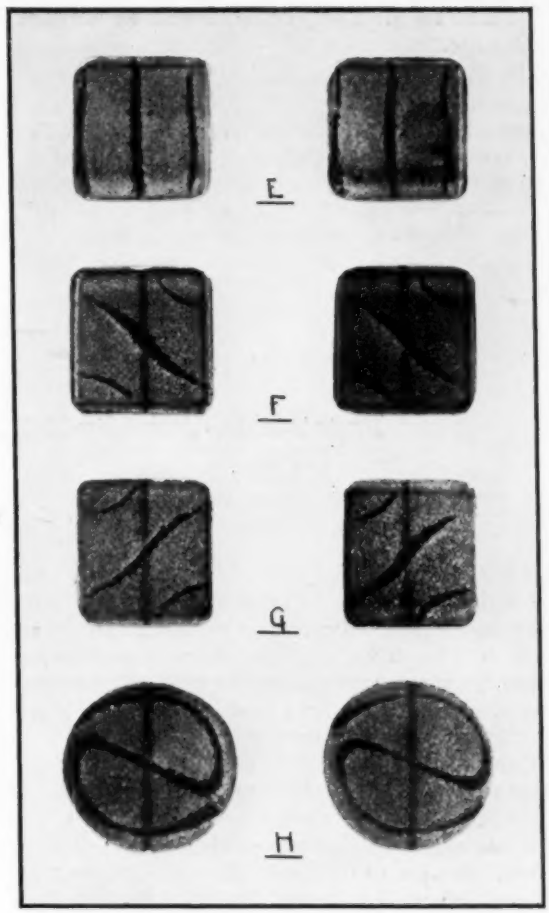


FIG. 2 (*continued*).

| | | |
|---|---|---|
| *E*—(*a*) 0.478 cm<br>(*b*) 3.00 cm<br>(*c*) 3.06 cm | bar—length 3.00 cm<br>diam. 0.75 cm | freq. 85.5 kc |
| *F*—(*a*) 0.478 cm<br>(*b*) 3.00 cm<br>(*c*) 3.06 cm | bar—length 5.06 cm<br>diam. 0.780 cm | freq. 50.75 kc |
| *G*—(*a*) 0.488 cm<br>(*b*) 3.01 cm<br>(*c*) 3.06 cm | bar—length 5.065 cm<br>diam. 0.781 cm | freq. 50.61 kc |
| *H*—(*a*) 0.491 cm<br>(*b*) 3.52 cm | bar—length 3.34 cm<br>diam. 0.761 cm | freq. 77.8 kc |

grounded to a brass plate above the top of the coil $L_1$, thus electrostatically shielding the crystal from the field of the coil. The crystal was placed upon the end of the bar with the bar directly beneath a nodal line (correct position found by trial). A pressure of approximately 30 grams was applied through a sharp stylus to the top of the plate. The pressure for optimum contact was very critical and varied for different bars. It was necessary to obtain the figure before the bar became appreciably warm since expansion changed the frequency.

As far as it was possible to tell from the vernier condenser and frequency meter, the frequency at which any crystal oscillated was just as sharp for the mechanical drive as for the electrostatic excitation. This is very different from a Chladni plate which will respond to a comparatively wide band of frequencies near a resonance point.

A comparison of the figures produced in these two different ways is shown in Fig. 2. The mechanical pattern is on the right and the electrostatic on the left. The resemblance between each set of figures is striking. Any random variations are caused by unequal amounts of sand in the two figures. The dimensions of the crystals and rods are given in each case. These frequencies are not the so-called fundamental frequencies of thickness vibration but are lower resonance frequencies to which the crystal will respond. The radiofrequency of these crystals was 584 kilocycles/second; the much lower frequencies at which the patterns were formed are shown in Fig. 2. The vertical line in each photo-

graph is for reference only and should not be mistaken for a nodal line.

The frequency vibration of a piezoelectric crystal is usually higher by about one percent than the frequency calculated from the elastic strain constants.[2] This discrepancy can be partially explained by a consideration of the equivalent electrical network. In this the quartz plate acts as a dielectric in parallel with the series circuit which represents the mechanical system. In these experiments no difference was observed. The experimental error in the comparison of the two frequencies is less than one-half of one percent, the chief error arising from the uncertainty concerning the exact action of a magnetostrictive rod when excited by a frequency which differs slightly from its natural period. The mathematical theory of these crystals will be found in the reference above.

[2] Hund, *Phenomena in High Frequency Systems*, p. 298.

## Penetration-Viscosity Relationship for Asphaltic Bitumens

R. N. Traxler and C. U. Pittman
*The Barber Company, Inc., Maurer, N. J.*

A RECENT paper by Saal and Labout[1] deals mainly with experimental evidence concerning the influence of the elasticity and adhesiveness of asphalts on the penetration test. In addition, and for the most part irrelevant to the experimental work, a lengthy criticism of our paper[2] concerning the penetration-viscosity relationship is given. It is this criticism which we wish to discuss.

When Saal and Koens[3] first published their relationship between penetration and viscosity, there was an inclination on the part of bituminous technologists to accept it as a quick and easy way of obtaining viscosity values for any asphalt. We, also, had hoped that a study of a number of different kinds of asphalt would lead to a simple, practical and accurate relationship between penetration and absolute viscosity. However, our investigations[2] of Native Lake and steam refined asphalts showed that one-third of the viscosities calculated by the equation

$$\eta = (5.13 \times 10^9)/p^{1.33} \qquad (1)$$

varied from the experimentally determined values by at least 15 percent. When plotted on a large scale the experimental penetration-absolute viscosity curves were found to be distinctly sinuous. The data given by Saal and Koens and offered again by Saal and Labout in Table IV were found to give the same sinuous type of curve. This is indicated by the fourth column of Table IV in Saal and Labout's paper where the ratios between calculated and determined viscosities are seen to pass through maximum and minimum values.

In an exchange of correspondence with Saal subsequent to the appearance of our study, elasticity was discussed; we agreed that it was an important property of many bitumens. At the same time (August, 1935) we stated "that the adhesiveness of the asphalt toward the needle as well as the elasticity influences the penetration test."

Saal and Labout state that our deviations were due to the fact that we overlooked the non-Newtonian and elastic properties of our asphalts. The viscosity values, which were obtained by the alternating stress method of Bingham and Stephens,[4, 5] were found to be independent of shearing stress after the sample had been worked at a high stress. Data which were sent to Saal in May, 1935 are given in Table I to show the behavior of two of our asphalts under different shearing stresses.

Recent experiments using a rotating conicylindrical viscometer on steam and vacuum refined asphalts of approximately the above penetration have shown that they possessed little, and sometimes no elasticity. However, some of these asphalts were slightly thixotropic.

Saal and Labout state that the two asphalts used in obtaining the data for their Table IV "are representative of the few origins of crude oil which give purely viscous bitumens." Traxler and Coombs[6] pointed out that the presence and magnitude of the anomalous flow properties (thixotropy, age-hardening,[5] elasticity, etc.) of asphalts depend upon (1) the *source*, (2) the *type and degree of processing*, and (3) the *temperatures and rates of shear* at which the measurements of flow are made. They gave data indicating that the flow characteristics depend more upon the method and degree of processing than upon the source of the petroleum from which the asphalt was prepared.

Saal and Koens[7] changed the consistencies of their two bitumens by varying the temperature. Our data[2] indicate that different results would probably have been obtained if they had changed the consistency by processing. Further, we have found[8] that different asphalts of the same penetration do not necessarily have the same viscosities as Eq. (1) infers.

From the statements given by Saal and Labout the reader must conclude that Eq. (1) applies only to asphaltic bitumens that exhibit no elasticity, thixotropy or anomalous

[1] R. N. J. Saal and J. W. A. Labout, Physics **7**, 408 (1936).
[2] R. N. Traxler, C. U. Pittman and F. B. Burns, Physics **6**, 58 (1935).
[3] R. N. J. Saal and G. Koens, J. Inst. Petroleum Tech. **19**, 176 (1933).
[4] E. C. Bingham and R. A. Stephens, Physics **5**, 217 (1934).
[5] R. N. Traxler and H. E. Schweyer, Proc. Am. Soc. Test. Matls. **36**, II (1936).
[6] R. N. Traxler and C. E. Coombs, "The Colloidal Nature of Asphalt as Shown by Its Flow Properties," Thirteenth Colloid Symposium, St. Louis, Mo., June 11–13 (1936).
[7] R. N. J. Saal and G. Koens, J. Inst. Petrol. Tech. **19**, 186–187 (1933).
[8] C. U. Pittman and R. N. Traxler, Physics **5**, 221 (1934).

TABLE I. *Viscosity data on asphalt at various shearing stresses.*

| Temp. °C | Shearing Stress (dynes/cm²) | Viscosity (poises) |
|---|---|---|
| Venezuelan Oil Asphalt (61 penetration, 100 grams, 5 seconds at 25°C). | | |
| 15 | 11,470 | $6.33\times10^7$ |
| 15 | 14,800 | 6.43 " |
| 15 | 31,200 | 6.13 " |
| 15 | 48,020 | 6.37 " |
| 20 | 14,820 | 1.70 " |
| 20 | 21,490 | 1.76 " |
| 20 | 28,330 | 1.68 " |
| 20 | 35,000 | 1.74 " |
| 25 | 4,150 | $6.35\times10^6$ |
| 25 | 8,300 | 6.31 " |
| 25 | 12,180 | 6.20 " |
| 25 | 16,200 | 6.38 " |
| Trinidad Oil Asphalt (60 penetration, 100 grams, 5 seconds at 25°C). | | |
| 15 | 13,460 | $6.47\times10^7$ |
| 15 | 20,070 | 6.45 " |
| 15 | 26,490 | 6.42 " |
| 15 | 37,330 | 6.51 " |
| 20 | 2,960 | 1.44 " |
| 20 | 7,900 | 1.45 " |
| 20 | 13,090 | 1.47 " |
| 20 | 18,060 | 1.44 " |
| 20 | 24,380 | 1.45 " |
| 25 | 3,750 | $3.38\times10^6$ |
| 25 | 7,740 | 3.40 " |
| 25 | 11,480 | 3.41 " |
| 25 | 15,090 | 3.33 " |

flow properties. This stringent limitation of the applicability of the relationship makes it worthless from an industrial standpoint since practically no asphalts utilized commercially lack all of these properties. The publication of such a relationship without careful qualification is to be deplored because many bituminous technologists, unappreciative of its limitations, may try to employ it to calculate the absolute viscosity of any asphalt in which they are interested. Since it is necessary to obtain complete data on the rheological properties of every different asphalt in order to determine whether or not Eq. (1) applies, of what practical use is the equation?

# Have You Read?

**Electricity.** W. L. BRAGG. Pp. 272+xi, Figs. 138. The Macmillan Company, New York, 1936. Price $4.00.

This book is adapted from the Royal Institution Christmas lectures. Besides the attraction of Professor Bragg's style there are many fine illustrations of unusual lecture demonstrations.

**Handbook of Engineering Fundamentals.** Edited by OVID W. ESHBACH. Pp. 1086+xii. John Wiley & Sons, Inc., New York, 1936. Price $4.00 for college edition, $5.00 for regular edition.

This handbook was prepared for the purpose of embodying in a single volume those fundamental laws and theories of science which are basic to engineering practice. It is essentially a summary of the principles of mathematics, physics, and chemistry, the properties and uses of engineering materials, the mechanics of solids and fluids, and the commonly used mathematical and physical tables, to which has been added a discussion of contractual relations.

**An Introduction to Nuclear Physics.** N. FEATHER. Pp. 214+x, Figs. 21. The Macmillan Company, New York, 1936. Price $3.00.

The book is an introduction and a summary: the chief ideas necessary for an understanding of current research in nuclear physics have been given with the aid of a few illustrative examples; on the other hand all the important results have also been included, in tabular form.

**Relativity Theory of Protons and Electrons.** A. S. EDDINGTON. Pp. 336+vi. The Macmillan Company, New York, 1936. Price $5.50.

In this book the author gives a connected account of a series of investigations in the borderland between relativity theory and quantum theory. It begins where his earlier book, *The Mathematical Theory of Relativity*, leaves off—at the point where in a survey of nature we encounter the phenomenon of atomicity. He states: "To our gross senses matter seems continuous, and it has been treated as continuous in the usual theory of relativity. Experiment has, however, taught us that it is composed of multitudes of units, and the theory is here extended to throw light on the existence and properties of these units."

**The Renaissance of Physics.** KARL K. DARROW. Pp. 306, Figs. 44. The Macmillan Company, New York, 1936. Price $3.00.

This book arose from a series of lectures before the Lowell Institute. Its scope is, however, considerably expanded beyond that of the lectures. Dr. Darrow describes the methods and ideas of modern physical research. Some of the topics treated are: Release of electrons from matter, magnets and moving charges, mystery of waves and corpuscles, and the technique of transmutation. The unusual clarity and grace of style of this book will be a challenge which other scientific writers will find difficult to meet.

# Here and There

The Bell Telephone Laboratories announce that Dr. Mervin J. Kelly has recently been appointed Director of Research. The Editor is glad of the opportunity of devoting the first space of the news section of the *Journal of Applied Physics* to Dr. Kelly. It was principally because of his efforts that this new journal has been started and it is under his leadership that the American Physical Society is arranging several conferences on various phases of applied physics.

Dr. Kelly joined the Engineering Department of the Western Electric Company, now the Bell Telephone Laboratories, in 1919 and since then has been continuously engaged in researches in electronics and in the development of thermionic devices of all types. In 1922 he was placed in charge of the vacuum tube development of the laboratories. In 1935, in addition, he was placed in charge of the development of transmitters and receivers for telephone instruments. Now, as Director of Research, he is in charge of all of the research activities of Bell Telephone Laboratories.

The Bell Telephone Laboratories announce also that Dr. Oliver E. Buckley has been elected Executive Vice President. Dr. Buckley is well known in the engineering world for his pioneering work on high speed submarine telegraph cables. He had direct charge of the application of permalloy tape loading, and the development of terminal equipment which increased the carrying capacity fourfold.

Dr. Buckley was chairman of the local committee for the very successful meeting of the Founder Societies of the American Institute of Physics in October. At this meeting he contributed the paper on page 40 of this issue. As Director of Research of the Bell Research Laboratories he had charge of fundamental studies in a great variety of fields. Among the more important may be mentioned acoustics, electronics, photoelectricity, magnetism, microphonic effects, conduction of current in solids and gases, piezoelectric crystals, wire and radio transmission, and chemistry.

Dr. Edward Bausch and Henry Ford shared honors on the evening of Tuesday, December 1, when the American Society of Mechanical Engineers made its annual awards for distinguished service in engineering and science, and "for great and unique acts of an engineering nature that have accomplished a great and timely benefit to the public."

Dr. Bausch received the A.S.M.E. Medal and Mr. Ford received the Holley Medal, the former established in 1920 and the latter in 1923. The A.S.M.E. Medal, according to a bulletin of the Society, is awarded once a year, "and that only for inventions and improvements of great merit in the technical and public sense." Among the previous recipients have been Hjalmar Gotfried Carlson, Dr. Robert A. Millikan, Dr. Ambrose Swasey, and other distinguished contributors to the progress of engineering.

Harold H. Beverage has just been elected president of the Institute of Radio Engineers. In 1929 Mr. Beverage joined the R.C.A. Communications, Inc., and is now chief research engineer. He is a member of the board of editors of the *RCA Review*, a quarterly journal of radio progress published by the RCA Institutes Technical Press.

The interest of industry in atomic physics is shown in the appointment beginning next May of Dr. Frederick Seitz to the research staff of the General Electric Company. Dr. Seitz is well known for his work with Professor E. Wigner on the constitution of solids. During the present school year Dr. Seitz is teaching at the University of Rochester. Together with Dr. Ralph Johnson he will prepare a series of nonmathematical papers on the application of the modern quantum theory of solids to matters of industrial interest. The first of these will appear in an early issue of the *Journal of Applied Physics*.

The 100th anniversary of the institution of the American patent system was celebrated November 23 in Washington. According to *The New York Times* the following were chosen to form a list of America's "Twelve Greatest Inventors:"

ALEXANDER GRAHAM BELL, the telephone
THOMAS ALVA EDISON, the electric light and the phonograph
ROBERT FULTON, the first commercial steamboat
CHARLES GOODYEAR, the vulcanized process for rubber
CHARLES MARTIN HALL, aluminum manufacture
ELIAS HOWE, the first practical sewing machine
CYRUS HALL MCCORMICK, the first practical reaper
OTTMAR MERGENTHALER, the linotype
SAMUEL F. B. MORSE, the electric telegraph
GEORGE WESTINGHOUSE, the air brake
WILBUR WRIGHT, the airplane
ELI WHITNEY, the cotton gin

Among the new developments shown were woven glass cloth, synthetic rubber, sun ray oven, and the use of polarized light to eliminate glare.

### Metals Research Conference

The rewards of cooperation in research in the field of metals through joint investigation of fundamental problems by physicists, metallurgists, and chemists will be discussed by leaders in these fields at a meeting to be held at the Massachusetts Institute of Technology on January 28 and 29 under the auspices of the American Institute of Physics and M. I. T.

Some of the more general papers to be presented are: "Research Problems in the Steel Industry," by Dr. E. C. Bain, United States Steel Corporation; "Inclusions in Ferrous Alloys," by Dr. A. B. Kinzel, Union Carbide and Carbon Company; "Flow Phenomena in Heavily Stressed Metals," by Professor P. W. Bridgman of Harvard; "Electronic Structures in Metals and Alloys," by Professor J. C. Slater, head of the Department of Physics, M. I. T.; "Corrosion," by Dr. J. R. Burns of the Bell Laboratories; "Elastic Properties of Ferrous Alloys," by Professor A. V. de Forest, of Technology; and "Chromium-Nickel-Iron Alloys," discussed by Dr. V. N. Krivobok of the Allegheny Steel Company.

In another group of papers various techniques and their applicability are to be presented, while in the third group some especially complex scientific problems met with in ferrous alloys will be discussed.

Arrangements for the meeting are in charge of Professor John Wulff of Technology, who will act as secretary, and Dr. Henry A. Barton, Director of the American Institute of Physics.

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Mr. W. W. Smith, manager of engineering, announces that the Westinghouse Electric and Manufacturing Company now has under construction at the Research Laboratories in East Pittsburgh an electrostatic generator which is designed to attain d.c. potentials of five million volts or more above ground potential. These high voltages are to be reached through the use of a large high-pressure vessel, of shape somewhat similar to an incandescent light bulb, mounted over the roof of a two-story laboratory building. The height of the vessel is 47 feet and has a 30 foot diameter hemispherical portion for the upper part. By means of air under pressures up to 120 lbs. per square inch, it will be possible to maintain steady potentials of five million volts and over on a 15 foot spherical electrode mounted in the center of the upper end of the tank. These voltages will be reached by using charged rubber belts in the modernized Van de Graaff version of an electrostatic machine. The spherical high voltage electrode, supported by four large micarta insulating columns, is further connected to the lower ground end of the vessel, by means of a segmented porcelain vacuum tube. This vacuum tube contains the lens electrodes which will make possible the focusing of protons, deuterons or alpha-particles into a small target spot about 35 feet away from the point of formation.

It is planned to use this high voltage generator in investigations of nuclear reactions throughout the region of available voltages. The work on nuclear physics will be under the general supervision of Dr. L. W. Chubb, Director of Westinghouse Research Laboratories, with Dr. William H. Wells in direct charge of the project, including design and construction of equipment. Dr Wells was graduated from Amherst, received his graduate doctorate degree from Johns Hopkins University and, prior to joining Westinghouse last June, was associated with the Physics Laboratory of the University of Minnesota.

A broad program of fundamental investigations on the chemistry and physics of glass surfaces to aid in the development of scientific apparatus and ophthalmic instruments has been started at Mellon Institute of Industrial Research by the Bausch & Lomb Optical Company, of Rochester, N. Y. The first studies will be concerned with the effects of environmental factors on the durability of the various types of glass used in optical instruments.

The Bausch & Lomb Optical Company, whose research in optical glass dates from the initial work of William Bausch, has maintained a fellowship at Mellon Institute since 1931 for research on various plant and production problems in optical technology. New developments in the past have included improved greases for optical instruments, cements for ultra violet transmitting optics, improved methods for making and testing mirrors and reflectors, and standardization of the sizes of fine abrasives used in grinding lenses.

Dr. Frank L. Jones, the fellow since 1931, will be in charge of the new investigations of the Bausch & Lomb Optical Company at Mellon Institute. An enlarged staff will continue the work on plant problems at the new research laboratory of the company in Rochester. Dr. Jones received his professional education at Bucknell (B.S., 1925) and at Columbia (A.M., 1927; Ph.D., 1931).

It has just been announced that Dr. George B. Pegram, Treasurer of the American Physical Society and Secretary of the Governing Board of the American Institute of Physics, has been made Dean of the Graduate School at Columbia University. The appointment is effective January 1, 1937. Dr. Pegram has been serving as acting dean since the death of Professor Howard Lee McBain last May.

Dr. Pegram has served on the Columbia faculty for the last thirty-six years in the roles of assistant, instructor and professor of physics. He is a graduate of Trinity College, now part of Duke University. He received his doctor's degree from Columbia in 1903. From 1918 to 1930 Dr. Pegram served as dean of the School of Mines, Engineering and Chemistry.

The Rockefeller Foundation has granted $655,000 to the Kaiser Wilhelm Institut to establish laboratories for research in pure physics and for the study of cellular physiology. Dr. Peter Debye has left his post at Leipzig to head the new physics institute which will be open soon.

A new journal appearing last year is *Geophysics*, "A Journal of General and Applied Geophysics" published by the Society of Petroleum Geophysicists. Vol. I, No. 1 is dated January 1936. There are two numbers per year. The papers published in the first two numbers are on geophysical prospecting methods and apparatus, theoretical phases and interpretation, examples of geophysical surveys, etc.

The Institute of Physics of Great Britain announces a Second Conference on Industrial Physics, March 18–20, 1937, at the University of Birmingham. The purpose of this conference is to promote the application of physics to industry by bringing to the attention of industrialists recent developments in applied physics and by providing opportunities for the interchange of ideas among professional physicists. The general subject is "Optical Devices in Research and Industry."

The College Physics Teachers of Michigan met at the Physics Laboratory of the University of Michigan, Saturday, December 5, at which time the new equipment for nuclear research was seen in action. Professor H. D. Curtis of the department of astronomy showed motion pictures of the development and decay of solar prominences taken recently with the new spectroheliokinematograph designed and built for the McMath-Hulburt Observatory of the University of Michigan.

The high tension apparatus of the University of Michigan for nuclear research has recently been stepped up to one million volts. The generator consists of five 200,000 volt transformers in series and was built under the direction of Dr. H. R. Crane of the physics department. The laboratory also has its cyclotron in operation at nearly 7,000,000 volts.

At the annual meeting of the American Society of Agronomy and the American Soil Survey Association held in Washington, D. C., November 17 to 20, the latter organization was combined with the Soil Section of the former to form a new organization of soil research workers to be known as the Soil Science Society of America. The Society is divided into six sections, one section being devoted to soil physics and one to soil technology and dealing primarily with the applications of physics and engineering to soil research. The other four sections are Soil Chemistry, Soil Microbiology, Soil Fertility, Soil Genesis and Morphology.

Among the problems of national importance now receiving considerable attention are two which are very closely related, namely, soil erosion and flood control, or the holding of our soils in place and the retention of moisture by soils. Applied physics in the hands of the agricultural scientist can do much toward the solution of these basic problems. Determinations of the basic structures of soils and their moisture retaining properties without organic matter or vegetation and in the presence of organic matter or vegetation are of fundamental importance.

Among the papers presented at this meeting dealing primarily with applied physics were the following:

Professor L. A. Richards and O. R. Neal of Iowa State College, described equipment by means of which they were able to obtain continuous records of the capillary tensions of soil moisture in the field. They found diurnal variations in capillary tensions at depths of a few feet due to variations in the rate of evaporation of water from the soil surface.

L. T. Alexander, T. M. Shaw and R. J. Muckenhirn of the Bureau of Chemistry and Soils, U. S. Department of Agriculture, reported preliminary results of the determination of the freezing points of soils, in which the change of state of the water was indicated by changes in the dielectric constant of the wetted soil.

L. B. Olmstead of the Bureau of Chemistry and Soils described the use of a small high speed air centrifuge of the Beams type to remove water from soils at a centrifugal force of 300,000 times gravity. The moisture contents of the centrifuged soils were of about the same value as may be obtained by exposure of dry soils to an atmosphere whose aqueous vapor content is slightly below saturation. A simple roller device for measuring the sticky point of soils was also described.

Professor Willard Gardner of Utah State College, by applying Darcy's law to the flow of water in soils, has worked out a plan for draining a given soil at minimum pumping cost by means of a properly distributed battery of wells.

C. A. Hogentagler of the Bureau of Public Roads, U. S. Department of Agriculture explained how, by means of certain physical tests of soil samples in the laboratory, one may ascertain how desirable any soil material may be for road subgrade or earth dam construction; and how the material may be improved by modification.

Professor C. E. Marshall of the University of Leeds, England, showed that the structure of clay minerals, determined by x-ray analysis, may be used to explain some of the physical and chemical properties of soil colloids.

A broad program of fundamental investigations on the chemistry and physics of glass surfaces to aid in the development of scientific apparatus and opththalmic instruments has been started at Mellon Institute of Industrial Research by the Bausch & Lomb Optical Company, of Rochester, N. Y. The first studies will be concerned with the effects of environmental factors on the durability of the various types of glass used in optical instruments. Dr. Frank L. Jones, the fellow since 1931, will be in charge of the new investigations. An enlarged staff will continue the work on plant problems at the new research laboratory of the company in Rochester, Dr. Jones received his professional education at Bucknell (B.S., 1925) and at Columbia (A.M., 1927; Ph.D., 1931).

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You can toss away the memorandum of that other phone number now as we have one of our own! And if you don't think I feel swell about it, you're not the smart brother I think you are. I get a kick every time I pass that telephone in the living room.
Kathryn
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# CURRENT LITERATURE OF PHYSICS

*THE Editors present for convenient reference in this section a list of those articles dealing with physics published in some thirty selected journals. Their definition of the scope of physics and their selection of the particular journals to be included are necessarily based on their interpretation of the wishes of the majority of the readers. The emphasis is placed on prompt mention and convenience of use rather than completeness. For many other excellent articles and publications, reference should be made to the regular abstract journals. Miss Margaret Shields, Physics Librarian at Princeton University, very kindly prepares the listings for the foreign language journals.*

## Annalen der Physik

SERIES 5, VOL. 27, NO. 5, OCTOBER 20, 1936.

Damping and Fine Structure in the Hydrogen Balmer Series. pp. 389–404. ***J. Meixner***

Percentage Yield of X-Rays *K* Fluorescence for C, N, O and Ne. pp. 405–420. ***W. Crone***

Positive Column in Mercury-Inert Gas Mixtures. pp. 421–458. ***K. Siebertz***

Two Conducting, Insulated Spheres in a Homogeneous Electrical Field. pp. 459–471. ***W. Krasny-Ergen***

Heat Conduction Laws in Moving Media. pp. 472–475. ***M. Lang***

SERIES 5, VOL. 27, NO. 6, NOVEMBER 7, 1936.

Applications of Magneto-Optic Kerr Effect. pp. 477–506. ***C. Zapf***

Hard Secondary Radiation of Cosmic Rays. pp. 507–531. ***H. Maasse***

Theoretical and Experimental Study of Transverse Vibration of Rectangular Plates with Free Edges. pp. 532–542. ***B. Pavlik***

Anomalous Exchange of Charge in Ion Collisions with Resonance. pp. 543–572. ***F. Wolf***

## Annales de physique

SERIES 11, VOL. 6, NOVEMBER, 1936.

Extreme Ultraviolet Spectrum of Mercury. pp. 561–574. ***L. and E. Bloch***

Experimental and Theoretical Study of Combustion of Detonating Gas at Low Pressure. pp. 575–662. ***P. Tauzin***

Visible Fluorescence of Mercury Vapor. pp. 663–750. ***A. Kastler***

## Astrophysical Journal

VOL. 84, NO. 5, DECEMBER, 1936.

Spectroscopic Examination of Meteorites. pp. 507–516. ***Arthur S. King***

Effects of Red Shifts on the Distribution of Nebulae. pp. 517–554. ***Edwin Hubble***

Spectrum of $H_2$ from λ3612 to λ4224. pp. 585–599. ***Norman A. Kent***

## Canadian Journal of Research

VOL. 14, NO. 11, NOVEMBER, 1936.

Studies in the Spectra of High-Frequency Discharges in Mercury Vapor. II. Comparison of Electrodeless with External Electrode Excitation. III. Modification due to Wave-Length. pp. 201–380. ***J. K. Robertson and R. H. Hay***

## Comptes rendus

VOL. 203, NO. 17, OCTOBER 27, 1936.

Conservation of Energy and the Shankland Experiment. pp. 777–779. ***F. Cernuschi***

New Measurements on Variation in the Zeeman Effect of Mercury with the Field. pp. 779–782. ***P. Jacquinot and G. Dupouy***

Absorption Spectra in the Schumann Region of Sulphur Vapor and Hydrogen Sulphide. pp. 782–784. ***L. Bloch et al.***

Debye-Sears Effect. pp. 786–787. ***J. Hrdlicka et al.***

Activation of Thullium by Slow Neutrons. pp. 787–788.

VOL. 203, NO. 18, NOVEMBER 3, 1936.

Structure of the Photon. pp. 864–866. ***T. Ionescu***

Application of Electron Optics to Mass Spectroscopy. pp. 867–869. ***L. Cartan***

VOL. 203, NO. 19, NOVEMBER 9, 1936.

Generalization of the Lorentz Transformation for a System of Corpuscles. pp. 924–926. ***J. Destouches***

Diffusion of Light by Neutrons. pp. 926–928. ***J. Solomon***

Absorption Spectra of Benzene and Its Derivatives in the Near Infrared. pp. 930–933. ***P. Barchewitz***

VOL. 203, NO. 20, NOVEMBER 16, 1936.

Quantum Mechanics and Relativity. pp. 983–984. ***B. Kwal***

Zero Method Use of Ballistic Galvanometer. pp. 987–989. ***G. Dupouy***

Photographic Method of Amplifying the Energy of Photons. pp. 990–991. ***A. Lallemand***

## Helvetica Physica Acta

VOL. 9, NO. 8, NOVEMBER 21, 1936.

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Radiation Field of Dipoles. pp. 649–650. ***H. Bühler***

Oscillation of Space Charge in the Magnetron. pp. 652–654. ***J. Müller***

Theory of Quenching Grid in Gas Discharge. pp. 655–677. ***F. Lüdi***

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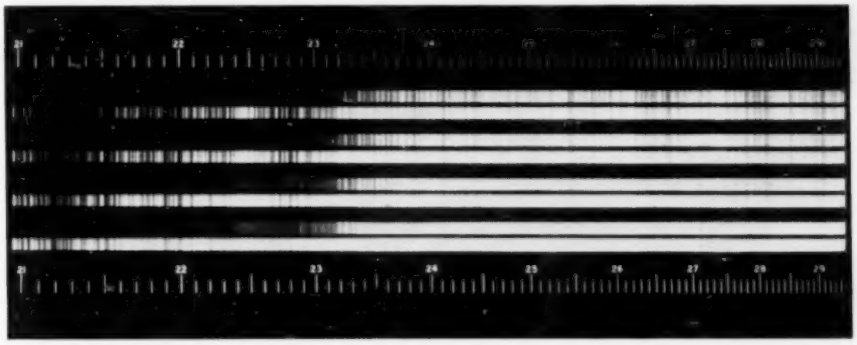

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Stroboscopic Phenomena in Propagation of Light Through Two Supersonics. pp. 678–688. ***R. Bär***

Essentials of a New Atomic Model. pp. 689–692. ***P. Guttinger***

Absorption Spectra and Life of Diatomic Molecules with a Free Bond. pp. 693–706. ***R. Miescher***

## Journal of the Aeronautical Sciences

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Nature of Wing Flutter as Revealed Through its Vibrational Frequencies. pp. 30–34. ***Katsutada Sezawa***

## Journal of Chemical Physics

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Ultraviolet Absorption Spectra of Simple Hydrocarbons. I. *n*-Heptene-3 and Tetramethylethylene. pp. 751–755. ***E. P. Carr and M. K. Walker***

Ultraviolet Absorption Spectra of Simple Hydrocarbons. II. In Liquid and Solid Solution Phase. pp. 756–760. ***E. P. Carr and G. F. Walter***

Ultraviolet Absorption Spectra of Simple Hydrocarbons. III. In Vapor Phase in the Schumann Region. pp. 760–768. ***E. P. Carr and H. Stücklen***

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Vibration Spectra and Molecular Structure. I. General Remarks and a Study of the Spectrum of the OH Group. pp. 772–778. ***R. B. Barnes et al.***

Relative Atomic Weight of Oxygen in Water and in Air. II. A Note on the Relative Atomic Weight of Oxygen in Fresh Water, Salt Water and Atmospheric Water Vapor. pp. 778–780. ***Malcolm Dole***

Kinetics of OH Radicals as Determined by Their Absorption Spectrum. I. The Electric Discharge Through $H_2O_2$. pp. 781–784. ***A. A. Frost and O. Oldenberg***

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## Journal of the Franklin Institute

VOL. 222, NO. 6, DECEMBER, 1936.

Report on the Work of the Bartol Research Foundation, 1935–36. pp. 647–714. ***W. F. G. Swann***

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## Journal of the Optical Society of America

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## Journal of Research of the National Bureau of Standards

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## Journal of Scientific Instruments

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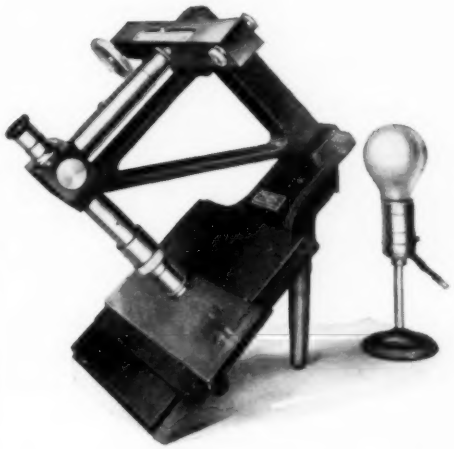

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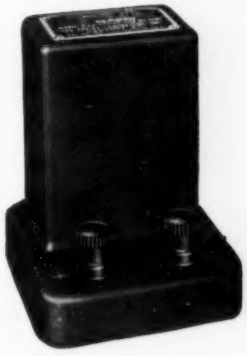

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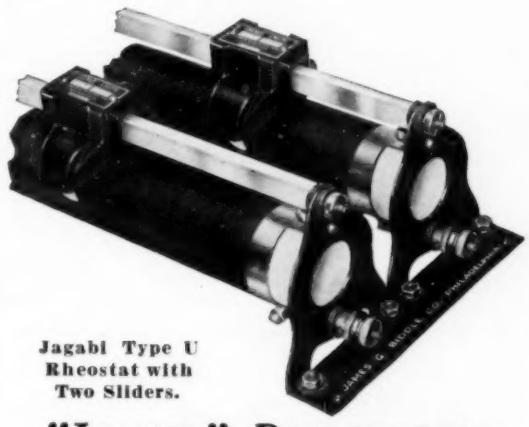

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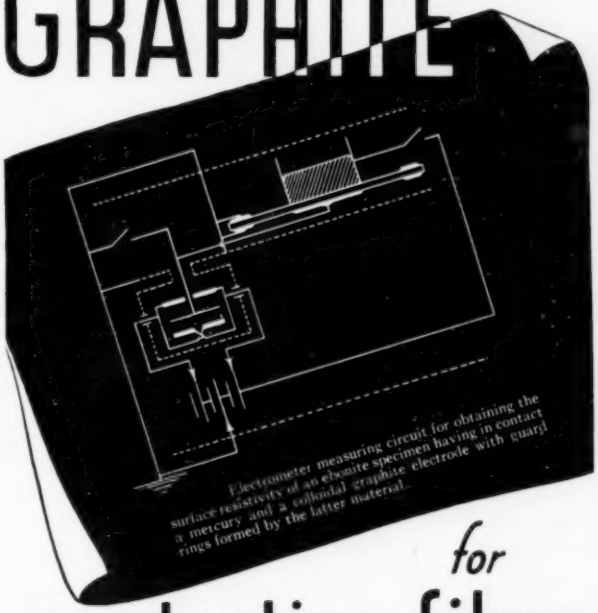

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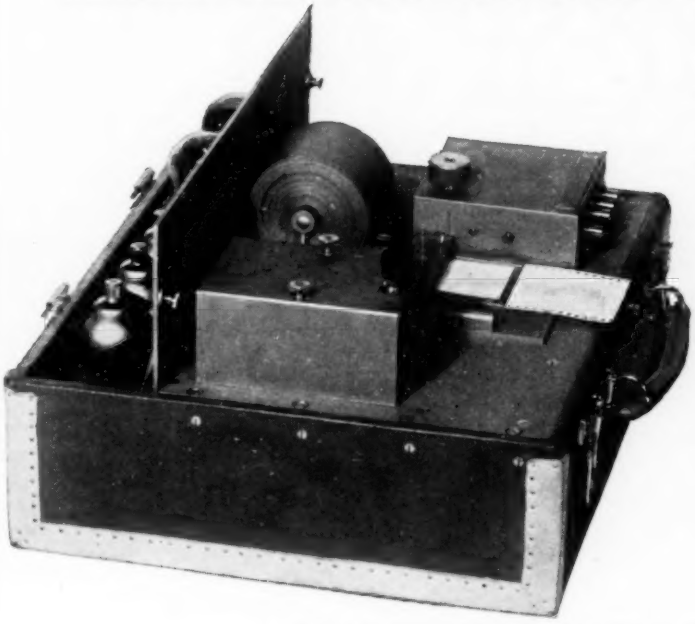

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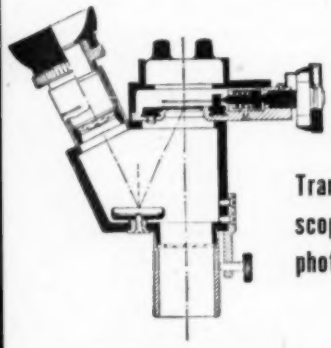

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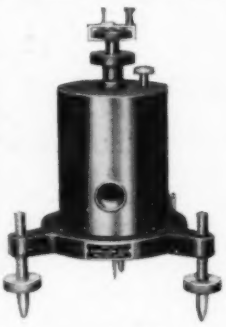

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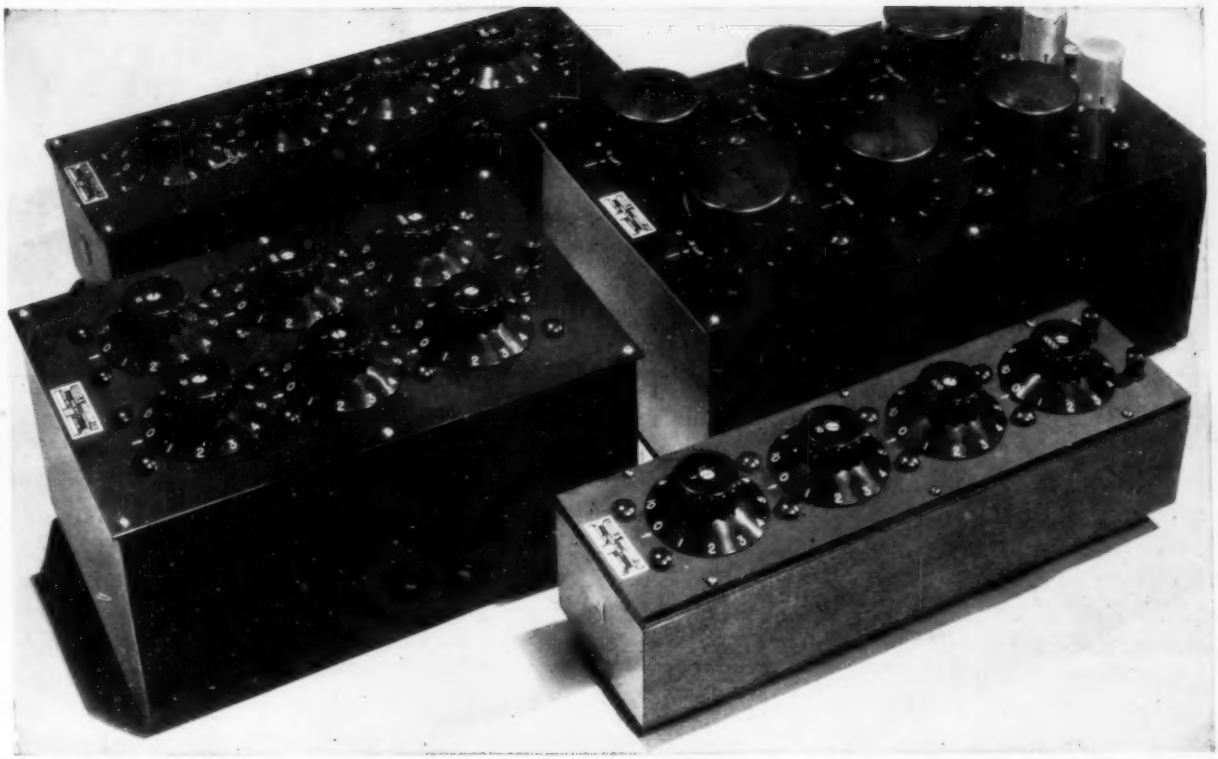

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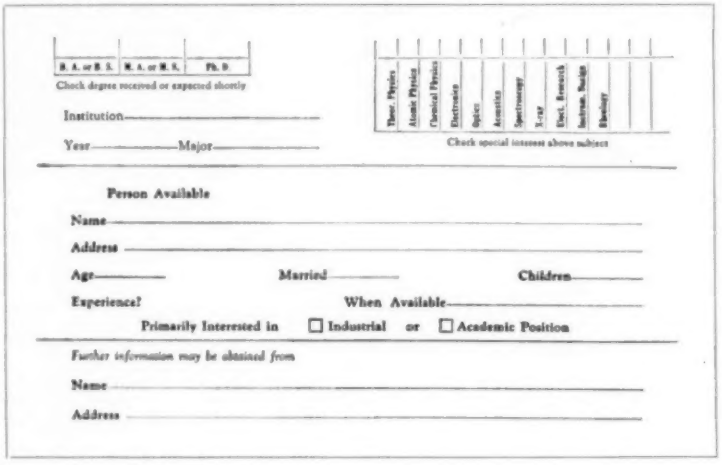
THE office of the American Institute of Physics receives from time to time inquiries from industrial executives for men who are trained in particular branches of physics. They are interested in knowing who are available and who have, or will have shortly, B.S., M.S., and Ph.D. degrees in physics. As a service to industry and also as a service to the members of the Founder Societies of the Institute, it is planned to initiate a placement file of those persons who are available.




To prepare such a list, the Institute is writing to the department chairman in each of the well-known educational institutions, requesting that cards similar in form to that shown here be filled out. These cards, when filled out, will give the necessary information for classifying graduates so that when a request comes in for a man trained in a particular way, it will be possible, without much difficulty, to suggest several names of those available and also the people from whom further information may be obtained.

It is essential that such a list be up-to-date. To aid in this purpose, the cards will be dated and removed from the file at the end of six months if they are not renewed. It will be requested also that the Institute be informed whenever anyone listed becomes unavailable. Since there is no charge for this listing, it is necessary that the clerical work be kept to a minimum. To do this the cooperation of all concerned is needed.

After these cards are filled in they will be filed in the Institute office with colored index tabs indicating the degree and particular interests of the person available. It will then be an easy matter to pull out the card of a man trained to fit a particular need. To prevent a large amount of correspondence, the Institute will not make any recommendations, but will merely supply names of applicants and references from whom further information may be obtained. This list will, of course, be available to academic institutions as well as industrial ones.

Suggestions for the improvement of this placement service, consistent with economy, will be appreciated.